A SKI INSTRUCTOR'S GUIDE TO THE PHYSICS AND BIOMECHANICS OF SKIING

by

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The material in this text is the result of many discussions about the mechanics and biomechanics of skiing. Therefore, I owe gratitude to many individuals who have stimulated thoughts and through their questions and comments given incentive for further study. My first attempt to set down the basic concepts was in 1972. The motivation for the early work was provided by the probing questions of Horst Abraham during the early days of the development of what is now known as the American Teaching System. My understanding of the subject has increased tremendously since then and I expect that it will continue to do so as this material enters discussion in the future. One lesson that I have learned since 1972 is that no matter how well I think I understand some particular aspect of skiing, there is always more to it.

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Finally, I would be remiss if I didn't mention the valuable contributions of the PSIA demo team members over the years. The names would fill the page, as these discussions range over the course of more than twenty years and five Alpine Teams, four Nordic Teams and two Snowboard Teams. The privilege of working with these outstanding ski professionals has contributed in a major way to my personal understanding of skiing.

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PREFACE

Skiing is a sport, a sport that is able to satisfy many diverse objectives for those who participate. On the most basic level, people start skiing for the sheer joy of movement that the sport offers. For some skiers, the joy and pleasure to be gained from free skiing remain the primary reasons to continue skiing. Others seek athletic challenges, whether in direct competition with other skiers, or in competition with themselves, the mountain and the conditions. Still others drop out, frustrated and convinced that the apparent effortless skill of advanced skiers remains an unattainable goal. They are convinced that they will never float down the mountain, but will remain forever locked into a struggle with unwieldy equipment in a hostile environment that appears to be dedicated to making skiing with pleasure and joy impossible. As with any sport, there are those who seek instruction as the way to speed the learning process. However, many newcomers to skiing persist in trial and error as the preferred path to their goals.

Old time skiers who have attained their personal skiing goals all seem to share the feeling that skiing is not really that complicated. If it is not really complicated, why the level of frustration experienced by so many people? Skiing is not a "normal" human activity. Skiers are required to perform intricate movements while sliding down a changing, slippery surface with their feet imprisoned in casts, attached to a couple of unwieldy boards. Yet, after sufficient experience, skiing becomes simple. The fact that this is so is a tribute to the adaptive learning nature of humans.

Can any written material speed this learning process? Perhaps, but the only way to learn how to ski *is* to ski. Thinking about and visualizing skiing may help you form clearer immediate goals and increase understanding, but eventually, you just have to go and ski. This text is intended to help the technically inclined increase their understanding of what is going on. It will not make you a better skier, nor will it *directly* make you a better ski instructor or coach. Increasing your understanding should help you simplify your instructions. Adding this understanding to physical experience gained from years of skiing will improve your teaching. How to effectively communicate this increased understanding, both verbally and physically, is the subject of learning/teaching theory and practice.

As you read the following pages, you will note that for the most part there are no specific "prescriptions" for what one should do when skiing, based on physical arguments. The focus is to provide an understanding of the tools with which one can reason about what is going on based on physics and biomechanics. And to do this, one needs to study the vocabulary and the concepts. For most people, these will not be familiar and thus great care is taken to develop these fundamentals. You will also note that quantitative examples are not given. Answers are not provided for such questions as: How fast can a skier really go? What specific muscles are used and to what extent in a given part of the turn? What are the actual loads on the body for a given turn? Such detailed answers depend on detailed knowledge of physical and anatomical data that is simply not yet available. Current research will provide some of the necessary data. Other parameters may be known, but not shared. For example, much is known about the sliding friction between a ski and a snow surface with different properties. However, this knowledge resides with the wax manufacturers, each of whom has an obvious vested interest in not sharing the information. Similarly, the behavior of skis is better understood by the manufacturer, but there is little reason to share this knowledge. Finally, there are phenomena in skiing that engineers do not even know how to measure. The focus of this guide therefore is to provide the tools and the reference material so that as more quantitative information becomes available, it can be discussed directly without having to write the basic explanatory material at the same time.

It is entertaining and challenging to contemplate skiing from a technical point of view. But remember, skiing is fun. Leave the "technobabble" at home when you pack your skis!

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1. INTRODUCTION

Discussions of "the mechanics of skiing" have been around for many years in one form or another, probably from the first time two people with a background including basic physics skied and then decided to talk about it. Science and technology are where they are today because people seem to have an insatiable desire to take a body of experience and observation and then attempt to quantify it.

Classical Newtonian dynamics as a means of quantifying human motion has occupied a prominent place in written expositions of ski technique. Of these expositions, the methodical and careful Swiss seem to have influenced American perception of the "mechanics of skiing" the most. The roots are in F. Schuler's 1932 *Ski Mechanik* with H. Brandenberger's 1958 *Methodik des Skilaufs und Ski Mechanik* being the direct parent of the 1964 PSIA publication, *The Official American Ski Technique.* Following this publication, the next major effort in the United States to systematically set down the biomechanical and physical basis for the analysis of skiing was J. Vagners' 1972 PSIA *Biomechanics Manual.* Following this, J. Howe's book, *Skiing Mechanics* in 1983 [3] provided an analysis from the vantage point of the ski manufacturer. In subsequent years, the interest in the application of the concepts of Newtonian mechanics and elements of biomechanics to the analysis of skiing has waxed and waned in inverse proportion to the interest in holistic and/or humanistic approaches to ski instruction. Recently there has been a resurgent interest in more technical material, as exemplified by G. Twardokens' book, *Universal Ski Techniques* [10]. (References not cited by number are out of print or difficult to obtain, thus are cited only to set the history of the subject).

Why should ski instructors study the mechanics of skiing? As with all sports, a deeper understanding of the basic laws governing the activity will lead to more objective views of what movements are effective and why. Sports instruction professionals have always attempted to base their understanding of any sport on the fundamental principles of kinesiology. (Kinesiology is the systematic study of human motion, from the analysis of simple walking to the most intricate gymnastic movements, and thus is the generic label for what we will refer to as the mechanics of skiing). For the ski instructor, the basic purpose of studying kinesiology is to provide a sound basis for analyzing human motion on skis. From an understanding of the fundamentals involved, a logical and sound basis for technique and methodology can be developed. The resolution of conflicting viewpoints on technical questions, teaching progressions and technique development should rest on kinesiological analysis rather than pragmatic argument. Also, it's fun to stretch your understanding and to challenge your mind!

Does this mean that to be an effective ski teacher one should become knowledgeable in all the complexities that make up the mechanics of skiing? The field is indeed broad. The mechanics of skiing includes the basic concepts from physics, elements of anatomy, how humans control motor activity, the response of ski equipment to various forces under different conditions, and the effects of different snow and slope conditions on different movements. Is an understanding of all these areas really necessary? No, we all know excellent ski professionals who have not formally studied these topics, yet are remarkably effective as instructors. They do, however, all share several characteristics. Whatever their background, they are all astute observers of how skiers move and have an extensive experience base in skiing as well as teaching. They all continue to experiment with different methods and closely monitor the progress of their students. The trademark is *simplicity*, these instructors know from experience that learning motor skills is best done in simple steps with minimal "information overload." This knowledge is the result of experience, and thus we could say that experience has taught these instructors the necessary elements of kinesiology without the burden of formal study of the subject. For these instructors, the material presented here can be considered superfluous. Who then is the intended audience of this material?

The material presented in the following pages will help instructors who wish to expand their understanding of human motion and the physics that shapes the motion. In and of itself, the knowledge will not make a better instructor. Remember that teaching style and how well it is matched to the student's preferred learning style, as well as sensitivity to the student, are more important than an understanding of physics and biomechanics. But increased understanding will help.

There are also many instructors and coaches who are inherently fascinated by the intricacies of skiing and wish to increase their own understanding. The material assembled here is for the individuals who ask: Why? How? What? Answers to such questions will not replace experience, but will speed understanding. For this to happen, you must answer for yourself the question: What is the reason for your interest in this information? "Why" is a magic word, and its uses vary from searching for specific information to it's use by a child to keep an adult talking. When you ask why, what kind of answer are you expecting? Practical, theoretical, technical, etc.? What do you intend to do with the answer received in response to the question? Have you increased your understanding of the subject that you questioned?

What is understanding? In school, the answer to this question is usually determined by your ability to answer questions on a test. So one might assume that the ability to answer questions by some "higher authority" or "expert" would be a measure of understanding. But this is really illusory. You may only be regurgitating something you studied *without* really understanding. Understanding means being able to test for yourself the truth of what you know, by observation and application to situations that you can experience yourself.

To meet this objective, I have some suggestions for how to read and study this text. The use of words, pictures, sketches, and experiments greatly enhances understanding of abstract concepts.

- When you think you understand a concept or explanation, explain it to others, using your own words and sketches. Your audience should include both persons who you feel have more experience in skiing or know more than you do as well as those who may not.

- Compare your explanations to those in this text.

- *Abstract concepts become real only if you gain personal experience with them and can relate them to physical reality*; thus I will suggest experiments throughout that you can easily perform to increase your understanding and allow you to personalize key concepts. Caution: what helps you to understand may not necessarily help someone else, each person's experience base is different. This is the way Newton developed mechanics - first simple experiments and observations, then more general deductions. "I have performed this experiment myself" says Newton, probably with reference to the natural philosophers of the day, some of whom were wont to describe the results of experiments they had not performed. Mechanics and biomechanics concepts are only useful to the skiing educator if he or she has personally experienced them and can pass on their essence to his or her students.

As you study the material, keep in mind the inherent and necessary limitations of physics/biomechanics explanations.

> - To be useful, physical theories and explanations cannot be "complete" or so comprehensive as to leave no room for the unknown. The power and utility of physical theories lie in their inherent incompleteness. We do not necessarily need (nor are able) to know *all* the details about what is going on to draw useful conclusions, *if* we know the nature of the answers we seek. For example, the existence of such system properties as linear and angular momentum, kinetic and potential energy, etc. derives its value precisely because the complete knowledge of the makeup of the system is not required.
>
> -"No understanding whatever is needed of anatomy, physiology, or the properties of leather to establish that one cannot pull oneself up by one's bootstraps. Indeed one can argue that science is only possible because one can say *something* without knowing *everything*. To aim for completeness of knowledge can thus be essentially unsound. It is far more productive to make the best of what one knows, adding to it as means become available." from Sir Hermann Bondi, *The Encyclopedia of Ignorance.*
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> - Realize that some of the concepts are difficult and subtle and that understanding will not necessarily come easily. After all, we are dealing with a subject that has occupied some of the best scientific minds of all time for over 400 years! Even professionals who work with mechanics concepts (be they engineers or physicists) continue to learn and gain new insights throughout their careers. Doctoral candidates in physics and engineering are still readily confused by seemingly simple problems, even after years of advanced courses in mechanics!
>
> - The vocabulary for the discussion of mechanics and biomechanics requires study. Many familiar terms from everyday use have specific and very particular meanings. I will pay particularly close attention to this vocabulary. It has been developed over the years to ensure clear communication. Each term has a long history since many people have struggled to clarify meanings. Again, even though the terms have precise meanings, your understanding should come from personal experiments and checking for understanding. Improper terminology leads to confusion.
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> - Some abbreviated terms have been introduced to improve the efficiency of communication, in a manner similar to the use of shorthand in note taking. But to communicate with the aid of shorthand conventions is only effective if each person has a clear understanding of the meaning of each shorthand symbol!
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> - Mathematics is the ultimate shorthand script in the communication about mechanics. Long, wordy, and often convoluted discussions about complex dynamical phenomena can be easily and compactly summarized with the language of mathematics. So as your inclination permits, invest the time to learn as much of the basic mathematics as you can. However, unless you have special training in advanced mathematics, some of the mathematical tools and techniques will remain outside your reach.

As your understanding grows, I caution you to never fall in love with your hypothesis, theory or explanation. Sooner or later, you will need to divorce it, as a more complete and beautiful hypothesis, theory or explanation comes along. Question authority. Just because someone with the "appropriate credentials" wrote it or said it, it is not necessarily true or correct. It could be true but incorrectly explained. It could be incomplete, or in error. If it doesn't make sense, keep asking questions. A general rule of thumb is: Definitions, the physical laws, facts about anatomy/biology, have been tested over many years and thus will be true, *applications* of these definitions, laws and facts can be in error. The errors can arise because the laws are incorrectly applied (errors in deduction) or because the knowledge required to apply the laws is incomplete. If one cannot verify the conclusions by experiment and observation, the errors cannot be corrected. Those who think their understanding is complete and that this understanding will never change labor under a dangerous delusion. Seek out alternative discussions and explanations of the same concept. By trying to compare two different explanations of the same concept, and perhaps trying to resolve these explanations with your own understanding, you will learn and gain a deeper understanding. Remember, for two seemingly different explanations, one need not necessarily be wrong. Beware of the dangers of oversimplified models. Much can and will go wrong unless you are careful.

The application of the basic concepts of physics (classical dynamics) to the analysis of skiing can take several forms: 1) Precise development by formulation of the complete mathematical equations of motion (a mathematical model) and deduction of results from these equations, 2) reasoning *qualitatively* based on the fundamental laws, 3) reasoning with the aid of graphics, and 4) reasoning *qualitatively* based on *results derived from* the fundamental laws. Each approach has it's advantages and disadvantages. The mathematical formulation requires fairly sophisticated tools of mathematics and thus is not readily available to everyone. Furthermore, there are severe limitations as to how far one can proceed without making simplifying assumptions which effectively negate the value of the analysis. The second approach is available provided that one studies the definitions carefully and integrates the discussion with simple experimentation. The graphical approach, using vectors and sketches, is a bit more involved, but is still accessible to anyone comfortable with visualization techniques.

The person seeking simplicity in physical explanations of skiing must first seek to gain an understanding of the key *concepts* of mechanics and develop the ability to think clearly about what is experienced in skiing. Note that the first emphasis is on concepts, not mathematical formulations. The basic concepts are critical, because (as noted above) "the basic laws of physics" and mechanics as a description of nature are really only approximations in the first place. These approximations attempt to quantify our observations of nature. This situation of course is in direct contrast to mathematics itself where everything can be exactly defined by formulating suitable postulates and thus building an exact system of mathematics. That is not to say that we should not use the methods and tools of mathematics to help us reason about the physical world. But as we do so, we should always keep the limitations in mind. The help we should expect from physics and biology is in aiding our understanding, not to justify preconceived ideas!

To set the context of the specific material on mechanics and biomechanics, I will review the technical and mechanical foundations of the American Teaching System (ATS). The highly technical discussions to follow form the background from which these foundations have been derived over the years. The basic concepts of skills, movements and the application of the skills concept to skiing need to be kept in mind as we go deeper into the material.

The traditional approach to the study of the mechanics of sport has been to study each constituent subject individually, i.e., the principles of mechanics, anatomy, physiology, and so on. I will approach the subject in the same way. Also, the traditional approach to mechanical analysis is to observe some activity and then to try to explain what is going on based on the applicable physical laws. The perspective I wish to advocate here is to view the activity of skiing as a *control and guidance* problem. What this means is that I will think of the skier as a moving system for which there is always a movement objective and that the skier takes appropriate actions to accomplish that objective. So we are always concerned with *cause and effect.* The skier desires to accomplish a particular result, takes some action with the body and skis, *then* interaction of the skis with the snow results in some particular form of motion.

This view includes the problem of guidance, defined as where and how the skier will move on the slope, as well as the problem of control. The problem of control is defined as: What must we do to remain upright while moving down the slope while reacting to all the disturbances we will encounter. The only forces available to the skier to accomplish these goals are the external ski-snow interactions, interactions of the snow and the poles, and to a lesser degree, air resistance. The skis, poles, muscles and limbs are the "control effectors" which are used to bring about just the right reactions from the environment (the snow) to accomplish the task at hand. (Control effectors are the means of implementing our desired control and guidance actions). The primary means of propulsion we have is gravity. This situation is similar to the problem of controlling the attitude of a glider, where the control surfaces are manipulated in just the right way for the airplane to maneuver as desired or to remain in nice, level flight in spite of the atmospheric turbulence it may encounter. For the glider, gravity is also the propulsive force. The control surfaces (rudder, ailerons, elevator) connected by cables to the aircraft controls are the control effectors. Upon movement of the control surfaces, they interact with the air and thus produce the forces necessary to accomplish the goal.

The control and guidance point of view is important to understand because the goal of instruction in skiing as in any other sport is to provide specific directions to the student that help the student improve his or her own performance. The more specific these directions are in terms of what muscular actions are desired the more effective the instruction. This does not mean that the instructor needs to be an expert in physics and anatomy. Rather, the instructor needs to be very clear about what is going on in terms of limb movements and understand the basic concepts of how motion starts and how motion is then controlled. Urging a student to "project the center of mass downhill," "steer the skis," or "use early weight transfer," provides absolutely no information as to just what the student is supposed to do with his or her body to accomplish these objectives. The key concept that I will return to time and time again is that all controlling and guiding actions come about as a result of what the skier does with the legs and feet (and to some extent the arms) with respect to the body. This in turn determines how the ski-snow and pole-snow interaction forces act in relation to the center of mass. We do things with these "control effectors" first, *then* something happens to the center of mass (guidance) and/or the orientation of the body in space (control). Motion cannot start *from* the center of mass.

Consider a simple example of what this means in terms of a specific skiing maneuver. Let's use the overworked concept of "projecting the center of mass down the hill." When you are in a turn, the muscles in your legs cannot all be relaxed if the legs are to transmit the reaction forces from your skis to your center of mass, otherwise, you would not be turning. To change from the existing turn to a new turn, the *first* thing you must do is relax the muscles holding you in the existing turn. What happens then, even if you do nothing else? With the turning force now no longer transmitted to the center of mass, it will move forward and downhill i.e. "project down the hill." If you ask students to simply relax the quads and abdominal muscles at the point when they feel the greatest tension in a turn, they will quickly understand what you are asking them to do. Direction to relax specified muscles or muscle groups is easily understood, specific, and to the point. "Project down the hill" conveys a desired action. To accomplish this action, one must understand what specific movements will yield the desired result. You do not need to know the specific anatomical structure of the body to give this instruction, but you do need to be aware of what goes on in your own body when you execute different skiing maneuvers or movements.

All maneuvers need to be related to muscle actions as specifically as possible if you are trying to communicate what you want the skier to do and that skier does not already have an experience base from which to translate the jargon. The key in this example, as well as many others I could provide, is that the motion *did not start from the center of mass*! This specific example could be continued to illustrate other enhancements that the skier uses, for example, activation of other muscle groups to amplify the motion. However, all such actions must follow the initial relaxation, no matter how brief, and all will originate in the musculature supporting the limbs. From a biomechanics point of view, this forms a closed kinetic chain, or sequence of specific muscle actions to accomplish a desired movement. Lack of relaxation of the antagonist musculature causes co-contraction, which results in stiff, robotic movements. Inability to selectively relax muscles is readily seen in the movements of beginning skiers.

To understand how any control and guidance system works, including the human system, we need to study the different components as well as how the system responds to different inputs. Thus we are led to the study of mechanics, anatomy and so on.

The first step in this study is to introduce the vocabulary and basic concepts of mechanics. The basic vocabulary must be understood before any meaningful analysis can be done. This discussion will use no formal mathematics. The only technical concepts we will need are the concepts of a vector quantity and the time rate of change of such a quantity. These I will introduce via simple diagrams and relate to everyday experience. Next, I will introduce the ideas of reasoning about ski mechanics from the point of view of work-energy relationships, which are derived from the fundamental laws of motion. The mathematical formulation of the equations of motion for the skier/ski system - rather forbidding material - will be relegated to an appendix. These equations are included for reference and to form the starting point for anyone who wishes to pursue the analysis of skiing using the mathematical models. (Those who are not mathematically inclined can skip this material.) The reason for including this material, which can be found in any college text on classical dynamics, is to provide a common nomenclature and conventions. This is useful for people who wish to pursue the mathematics. Furthermore, the mathematics are necessary to clarify some of the conceptual issues, for example the nature of centrifugal and other inertial forces.

The next major section will then deal with the vocabulary and concepts of anatomy and physiology (biomechanics) to the extent that we need for application to analysis and understanding of skiing. Application of biomechanical and dynamics concepts to the issue of skier alignment and the problem of effective and efficient use of the equipment will be covered next. The concluding section will address the control problem: How humans control and guide motion, what are the basic limitations, and what these limitations imply for learning any new motor skill.

2. A REVIEW OF ATS TECHNICAL AND MECHANICAL FOUNDATIONS

The American Teaching System is founded on four major technical and mechanical components: 1) The skills concept, 2) a skiing model and an appropriate set of Center Line images illustrating the skiing model (for use as a reference in developing lesson plans), 3) the relationship between biomechanics and the skiing model, and 4) the movement assessment techniques used to shape the learning experience. These technical and mechanical components are supplemented by a teaching model as well as information on guest services, safety, the mountain environment to form the complete American Teaching System. The following sections will define the technical and mechanical components and the terminology used. Other aspects of ATS are covered in other PSIA publications.

2.1 THE SKILLS CONCEPT

The concept that motor skills are basic building blocks is central to the American Teaching System. What is a skill? Fleishman (1969) defines skill as a "level of proficiency on a specific task or limited group of tasks." Singer (1975) cites a definition from the Winston Dictionary as "skill is the knowledge of any art together with the expert ability to put that knowledge to use." According to Fleishman, ability, on the other hand, is thought to be a more basic characteristic which may be used in developing skills. From this we can see that "**skills** (are) movements that are dependent on practice and experience for their execution, as opposed to being genetically defined". (Schmidt, 1988). Thus a specific skill is acquired through practice and refined through experience, while the absolute level of skill that may be attained depends primarily on a certain collection of abilities.

An understanding of the skills concept allows the instructor to develop lesson plans and adjust those plans as necessary to best help students progress. A rigid dependence on a set of maneuvers or a strict maneuver-based progression will interfere with learning and lead to frustration. Remember, you are teaching *people*, and each individual brings a different set of attributes to the sport at hand—different abilities, sports and movement experiences, and attitudes toward the learning situation. The principles on which to base the mechanics of your teaching, therefore, must be fundamental and adaptable to the variety of situations you will encounter.

A clear understanding of the skills concept and the related concept of ability is necessary because these concepts apply to all of the skiing disciplines: alpine, nordic downhill, nordic cross country, and snowboard. (Ability and the skills concepts are explained in detail in appendix I.)

The value of introducing alternative movement progressions and changing the emphasis on particular movement patterns in a lesson is best determined by checking for skill development. The guiding principle is that the maneuvers you teach should provide building blocks for acquisition of skills. An exercise has value when it strengthens one or more of the basic skills that is deficient.

There have been a number of changes in how the skills concept is viewed in ATS since its initial introduction. The current understanding of skills differs somewhat from the early descriptions in that *all are now movement focused* and *the concept of control* is integrated in the skills definitions. (Specific definitions of the technical terms in the skill descriptions are given in later sections; consult the index.) The four fundamental skills are described briefly as follows (with more elaboration in the subsequent paragraphs):

- **Balancing movements** are the movements required to keep the body in equilibrium when it is acted upon by external forces. Body equilibrium is to be interpreted as a desired orientation with respect to the slope. The external forces may be the result of deliberate actions on the skier's part (turning the skis or adjusting edge angles or using the poles), or they may result from disturbances (uneven snow surfaces or changes in terrain). The balancing movements may involve relatively gross body adjustments or almost imperceptible adjustments, depending on the circumstances.

- **Rotary movements** are movements involving rotation, or a tendency toward rotation, of either the body as a whole or of one part of the body relative to another. As is the case with balancing movements, rotary movements may be subtle or strong. However, rotary movements may be either rotation enhancing or rotation resistive, depending on the situation and the skier's wishes. For efficiency and stability, it is generally desirable to use the lower body to generate rotary movements.

- **Edge-control movements** are movements which affect the way the edges of the skis interact with the snow surface. Instructors introduce the concept of "control" with edging movements since the edges are the active interface between the skier and the snow. These movements, along with the pressure control movements, ultimately determine the forces from the ski/snow interaction that turn the skis.

- **Pressure-control movements** are movements used to regulate and adjust the pressure that the skis exert on the snow as they move on or through the snow.

When discussing balancing movements, people often talk about "balance" as the skill. Also, the terms "static balance" and "dynamic balance" are often used. As we shall see later on (section 3.10) these terms are closely connected to the concepts of force and moment equilibrium. Static balance usually is used to imply a balance of forces on the body such that there is no resultant motion. Dynamic balance loosely refers to the body being maintained in a desired orientation with respect to the environment while in motion. Consult the section on the interpretation of the laws of motion (section 3.10) for a discussion of these concepts which includes the required definitions as well.

There is also some debate as to the classification of balancing as a skill. As indicated in appendix I, there are several ways that one may view skills. Typically, motor skills can be characterized by the following features: 1) They are goal or task specific, 2) they require body and/or limb movements, and 3) they are performed voluntarily. One might argue that the movements required to maintain balance (e.g. a desired posture) are not voluntary but more reflexive in response to perceptions of loss of balance, and hence should not be considered a skill. However, nothing is lost if one thinks of the balancing movements as a broad category of skills essential for successful skiing (c.f. Schmidt, 1988).

Rotary movements are most often interpreted in skiing to mean movements about the longitudinal (head to feet axis, defined as the intersection of the frontal and sagittal planes) of the body. Also, rotary movement skills are usually thought of as creating rotational motion. However, depending on the situation, there are many options: Enhancing rotary movements (creating), resisting such movements (reacting), or blocking rotation. Blocking means to stop rotation that exists and may be effected externally through pole use or internally, by appropriate use of body musculature.

The definition of pressure control movements identifies those movements that are used to regulate and adjust the pressure between the skis and the snow. Active pressure control will involve such actions as increasing or decreasing the pressure on the front, back, or the middle of the ski(s) through use of leverage exerted by the lower legs against the boots and bindings, or body lean. Other mechanisms can involve vertical or lateral displacements of the body mass through muscular actions, for example, as the result of flexion or extension. Where on the ski(s) the pressure is exerted will be determined by a combination of these body movements and the dynamics of the situation.

Another mechanism for pressure control comes from use of the terrain. Depending on how the body movements are timed in response to changing terrain, one may have absorption, rebound, or retraction. Absorption involves flexion/extension movements of the body to absorb and even out the pressure felt by the skis as a result of turn dynamics or terrain variations. Rebound is the recoil (springing back) that the body and skis experience at the proper release of the elastic energy stored in the deformed ski(s). Finally, retraction is the action of pulling the legs up under the body by contracting the muscles of the lower body. Retraction movements are used to actively absorb pressure increases due to terrain changes or the effects of turn dynamics. The difference between absorption and retraction movements is that in absorption we react to perceived pressure changes and in retraction we move in anticipation of pressure increases that would occur if we did nothing.

All these pressure control mechanisms are useful and may be used individually or in combination to aid in the initiation, control and finish of turns. While there may be situations when it may be beneficial to use one form of pressure control over another, one should not stress such emphasis. ATS emphasizes learning and using all options.

Edge control movements address all the movements that affect the way the edges interact with the snow. For example, edge control might mean the action of adjusting the angle of the edge(s) to the snow. Or, it might mean slight fore-aft movements that control how the edges move with respect to the snow. Under edge control, one can also discuss the movements involved in edge change. Edge change is defined as the action of tilting from one edge to another, that is, changing the edge that is in primary contact with the snow. This action can be performed with the skis in contact with the snow or without such contact. We may change from one edge of a single ski to the other edge of the same ski, or an edge of the other ski. Or, the edge change action may involve both skis in that we change from one set of edges to the other.

The action of changing edges is inescapably linked to pressure changes, particularly so if we move from one carving turn to another. To change edges in this situation, the skis must first lose reverse camber and this will result in pressure changes.

Instructors need to elaborate on how the fundamental skills apply directly to the events and actions which take place during turns. This must be done for all levels of skiing, from introductory to advanced levels. Whenever possible, descriptions of desired actions should be specific and refer to muscular movements that students can feel and understand. In this way, fundamental skills become a part of analyzing skier actions and the subsequent skiing improvement tasks and instructions. What this means is that an instructor needs to spend time skiing all maneuvers, feeling what he or she does, and attempting to identify specifically what is done with the body to elicit particular results - movement analysis, but on yourself!

When skills are related to movements in this way, an underlying value system, or model, for "good skiing" is defined. Determining such a model may seem difficult since the guidance and control problems encountered in specific situations will vary and may appear to require individual solutions (for example, recreational skiing versus racing and groomed run cruising versus steep terrain skiing). Also, not all skiers experience the full variety of situations, nor seek them out, and consequently have a limited reference base. Thus, one might expect that individual, personalized views of good skiing would preclude establishment of a suitable skiing model to serve as a practical reference for teaching and the implementation of the skills concept.

I claim that all good skiing has a characteristic signature that allows definition of a useful model. *The characteristic signature of good skiing shows rhythm, flow of movement, efficiency, power, sensitivity, and precision.* These qualities serve as the departure point for defining a skiing model. To be a universally valid model, it must be applicable to all levels of skiing. Even unsophisticated observers (who may have little or no knowledge of the sport) have little difficulty in identifying skiers who exhibit the qualities I have identified, so this characterization appears to be universal.

You must recognize that the maneuvers you teach are seldom ends in themselves. They are tools for overall skill enhancement and are representative of typical stages of skill development. Exercises and maneuvers that are well-thought-out should emphasize edge control, pressure control, and rotary movements of the legs and torso. They should also encourage learning to balance while moving across and through the snow. Keep in mind that there should be continuity in skill development so that exercises and maneuvers develop basic skills in a consistent manner from the beginning to the advanced level. Also remember that the central problem for the learner is how to balance while in motion and while performing the complicated muscular movements required to guide the motion. As you develop and use exercises, be sure that the actual muscle and skeletal involvement are consistent with the actual skiing situation for which you intend to use a specific exercise.

2.2 THE SKIING MODEL AND CENTER LINE

To anchor the technical and mechanical foundations, I will define a skiing model. What are the components of such a model? They are, first, its qualities—the distinctive signature described above. Next, there are the fundamental building blocks—the skills identified above. Then, there must be guidelines for using the building blocks when applying the model. Finally, there must be guidelines for applying the fundamentals so both the student and the teacher clearly see the interrelationship of the various tasks and exercises used to improve the student's skiing.

There are multiple models possible. After all, models are constructs to help one visualize a given situation. So it is reasonable to assume that one can establish models for free skiing, extreme skiing or racing for example. The primary focus for instructors is recreational free skiing. This focus requires that we consider the full spectrum of skiing levels from beginner to expert. While inspiration may come from studying world class racers in a race course, a better model for instructors comes from studying these racers free skiing.

To help define a skiing model for recreational free skiing and provide a reference structure, the concept of Center Line images has been introduced in ATS. (Center Line images have been identified for all the skiing disciplines.) These images are included in the teaching guides developed for all skiing disciplines. The Center Line images serve as a reference when evaluating skill levels at particular phases of skiing, a reference which helps both instructors and students understand the students' level of achievement at any stage of development. The concept of introducing consistent images and the concept of a reference line has been a part of ski teaching for a long time e.g. the "red line" of Kruckenhauser in the Official Austrian Ski Technique.

The specific maneuvers which show skill progression from elementary skiing to high levels of proficiency make up the Center Line images and provide the reference (structure) instructors and students need. The selected maneuvers should be consistent in the way they showcase fundamental skills and form a logical progression from simple to complex movements. Furthermore, the image they convey should reflect the characteristic signature of good skiing. The specific maneuvers selected to define the Center Line then serve as check points during the suggested instructional progression.

The majority of instruction is carried out at the lower levels, and the foundation established at these levels serves as the foundation for skill development at the upper or expert levels. Consequently, the instructor should view the Center Line images as demonstrated on groomed snow as an *aid* in focusing lesson plans. While the objective is efficient and effective skiing under all terrain and snow conditions, learning usually starts on the best snow conditions available at the time. The instructor and student will usually operate in a mutual learning environment, with the basic characteristics of good skiing guiding their (mechanical) activities rather than any specific Center Line image.

An important part of any lesson at the expert level is tactics defined as skillful methods used to gain a desired objective. Thus, specific mechanical content or maneuvers may indeed take a less prominent role in the lesson. Greater student progress can often be achieved by first helping the student make better terrain choice or line choice, then focusing on movements.

Center Line images should not become the content of your lessons. ***We do not teach the Center Line, and our customers do not come to lessons with the personal goal of learning a specific Center Line maneuver.*** What we do teach are movements and movement patterns that provide students with a sound foundation that will ensure success in whatever skiing situation they may find themselves. In some cases, you will have students who wish to improve specific aspects of their skiing, such as carving, speed control, and linking turns. You can help students accomplish their goals while still developing the versatile skills base they need.

As instructors, we need guidelines for applying the fundamental skills at each level of development. These guidelines should identify the common features of each skill for each level of the Center Line, as defined by the selected maneuvers. Furthermore, the guidelines should remain valid at the expert level to help evaluate the effectiveness and efficiency of movements in any situation that may be encountered. Finally, these guidelines should recognize how anatomy, physiology and physics influence human motion. These considerations lead me to propose the following guidelines.

Balancing Movements. Balancing movements are more efficient and effective if:

- there exists a functional relationship of the legs. We seek a relaxed athletic stance which allows efficient movement of the legs and torso. "Functional relationship" means that the legs do not interfere with each others actions and movements. For example, such interference occurs when one knee is tightly locked to the other in an attempt to maintain a parallel relationship of the skis. "Functional relationship" also means that the use of one leg can aid in the function of the other in a specific movement task.

- the stance is fairly tall, which allows for better skeletal efficiency. When the skeleton holds the body upright with minimal muscular contribution, the metablic demand is low. A crouched stance which significantly tenses abdominal and back muscles will inhibit movements. However, a slightly tensed muscle has an increased rate of conduction which translates into a decrease of movement time for the muscle. Such a muscular state is characteristic of what we usually interpret as an “athletic stance”.
- balancing actions involve the actions of the whole foot (neither toe nor heel bias) for both feet; this develops the ability to work the entire ski.
- the upper body is disciplined and has a dynamic relationship with the skis. "Dynamic relationship" implies that the upper body never assumes a totally static, immobile state.
- turns are linked, and there is a continuous flow of the center of mass, which produces and maintains rhythm. 'Flow of the center of mass" means that as long as we are moving and turning, we avoid momentarily stopping the body, then accelerating again.

Rotary Movements. Rotary movements are more effective and efficient if:

- the rotary movements are used to support active guidance of the skis throughout the turn. "Active guidance" means that the muscles of the body are active throughout the turn to continuously shape the turn.
- the rotary movements are used to complement pressuring and edging movements.
- muscular actions actively guide the skis throughout each turn, which greatly enhances the flow of the turn. At no phase of the turn does the body assume a static or passive stance in relationship to the skis. "Flow of a turn" is meant to describe a smooth evolution of the turn .

Edge Control Movements. Edge control movements are more effective and efficient if:

- the skis are guided onto the edges, and subsequent edge adjustments assist in achieving the desired turn shape. "Guiding the skis onto the edges" means that the motions are gradual and not abrupt, unless required for a specific purpose such as hard edge sets in short turns on steep terrain.
- the movements are adapted to the equipment used, the snow conditions and the terrain.

Pressure Control Movements. Pressure control movements are more effective and efficient if:

- the movements made to shift pressure to the inside edge(s) as the turn develops are smooth and progressive.
- flexion-extension, fore-aft, and lateral movements complement other actions in the control of turn shape. (Action with, and reaction to, terrain variations contribute to these movements.)

In the above discussions of the effectiveness and/or efficiency of movements, I have used the terms "guide" and "guidance." A working definition of "guide" is: To direct motion by physical action, to use muscular movements to direct motion. A closely related term is "steering," which is defined as the act of *directing the path of the skis by muscular actions*. I wish to distinguish these terms in the sense that "guidance" should imply a more subtle action than "steering." Steering implies that the principal cause of the changes in the path of the skis is muscular, while guiding implies that the effects of the way the snow acts on the skis are primary and guidance is merely an aid to this action. Pivoting of the feet contributes a steering action in the sense that I have used steering. However, steering should be understood to mean a combined motion involving rotary motion in the hip joint. Under steering action, if one takes off the ski, the ski boot will draw an arc in the snow; pivoting will leave a "bow tie" or "butterfly" mark.

The suggested guidelines are intended to help the instructor focus lessons on specific goals and to help him or her quantify student-desired outcomes. Because the guidelines apply in a consistent manner to all maneuvers, considerable freedom exists in the choice of appropriate tactics. The instructor is faced with a large array of choices during the course of a lesson, depending on factors such as student progress and condition variations.

Note that these guidelines are not specific as to what muscles are involved. At the time of this writing, the problem of identifying specific muscles involved in different phases of a ski turn is the subject of research. Recording of muscle activity has been done throughout a turn. However, it seems that the classification of the phases of a turn conventionally used by ski instructors does not correspond well to electrical activity in the muscles. So the jury is still out. In the meantime, thinking about turn mechanics with the aid of a general classification of initiation, control and finishing phases is still useful. Also, identifying what you are feeling in your body during different movements and the relationship of these movements to where you are in a given turn is useful for instruction.

Also, the guidelines do nor describe in detail the movement patterns to achieve the desired goals. These issues are the subject of technical manuals in each discipline. These are the "how to" descriptions of skiing maneuvers at each level of development. To make the connection to desired muscle activity, you must go out and ski various maneuvers, focusing on what your body is doing. Remember, abstract concepts only become real when you personally experience them!

2.3 MECHANICS, BIOMECHANICS, THE SKIING MODEL, AND SKILLS

In reviewing the skill definitions and the guidelines for applying the skills concept to skier development, it becomes apparent that the key concepts are all biomechanical. There are the movements themselves, control of the movements, the characterization of the movements, the effects of differing movements, and the shaping of movements as the skill levels progress from beginning to expert. Thus, a deeper understanding of the skills concept and the appropriate skiing model to use as a reference requires looking at the biomechanics involved. Biomechanics rests on mechanics (the action of forces on the body as well as the generation of forces by the body) and anatomical function (the skeletal system, muscles, kinesthesia).

I have used the term "biomechanics" tacitly assuming that everyone knows what it means. To be certain, I will define what I mean by biomechanics in this text. The term itself is a composite and a relatively recent addition to the English language (you won't find the term in a 1960 edition of *Webster's Collegiate Dictionary*, for example.) "Biomechanics" today means the study of living creatures in motion, in particular, humans in motion. In the seventies and early eighties, biomechanics was primarily involved with measurements and some limited modeling to predict human motor variables that cannot be measured directly. In the nineties, the focus has shifted to issues of motor control in human movement. Currently, a major goal of the study of biomechanics and motor control is to assess and understand human movement. This goal is becoming more realizable as a result of progress in understanding of the basic physics involved, advances in modern computing technology, measurement and measurement processing technology, and understanding of how muscles work. This view is consistent with my approach to skiing as a guidance and control task, as noted in the Introduction.

Certainly one way to apply biomechanics to skiing is to base all analysis on the traditional Newtonian approach used in engineering and physics. That is, start with the identification of all the forces acting on the skier and/or skis, draw appropriate diagrams which display how and where these forces act on the skier and/or skis, and then analyze the situation after deciding which motion to study. Because I realize that there are individuals who wish to pursue this approach, I have included the relevant information in this publication c.f. appendix II. This approach is quite complicated, as a reference frame must be identified, and all forces must be expressed in the selected reference frame. Furthermore, the forces involved are all continuously changing in time and the body generated forces may be the result of different muscular actions, many of which produce the same overall effect. The situation rapidly becomes quite confusing, even for individuals trained in the analysis of dynamic systems. The usual temptation is to assume some simplified model or to identify what one believes to be a key characteristic of the situation and then build the analysis based on these assumptions. This approach is sometimes useful, sometimes merely confirms something that one knows from experience or, more often, leads to erroneous conclusions. Nevertheless, for those readers who wish to use this approach, I have provided the necessary concepts, definitions and mathematical expressions. A word of caution: Discussion of skiing using such precise formulations should only be done at the highest levels by people trained in the language of mathematics and physics. This type of discussion should never be used in examinations or with students!

An alternative approach suggests itself when we realize that the primary help we can derive from biomechanical analysis is to aid in thinking about the effectiveness and efficiency of movements for selected tasks. After all, if a skier *intends* to make a turn in some direction, *does* something with the body and the skis, and then *turns,* then there is nothing *wrong* with the movements used. What an instructor needs to be concerned about are the qualities of the movements involved and whether or not the results were satisfactory to the person who made the turns. Remember, viewing skiing as a guidance and control problem always requires that objectives for the motion be kept in mind. What are the objectives for the situation: Efficiency? If so, then one needs to decide if the movements were as efficient as they could have been. Appearance? If so, did the movements look good? And so on.

The previously identified characteristics of good skiing all focus on the *qualities of the turns and movements*, not on whether a turn actually happened or not. Granted, the first concern of students is whether they can make the turn where and when they want to. Once that happens, however, the value of instruction is in shaping the qualities of the turns and extending the range of conditions in which students can use the turns they know how to make. *The quality of motion, in fact, is what we are judging when we look at someone skiing, whether in a certification setting, a teaching situation, or just casual observation on the slope*. The term *quality* implies a criterion of judgment so one should define the criterion one is using. The criterion can be efficiency or effectiveness or appearance or whatever one decides is a significant measure for task or movement evaluation.

To judge movements according to effectiveness, one must state a measure of performance. There is no single measure of performance in skiing. For example, we can define separate measures of performance or criteria for racing, exhibition skiing, or extreme skiing. Having done so, then we can form judgements about effectiveness in relation to the stated criterion.

When judging quality of movements, we can consider the issue of efficiency. Efficiency is clearly related to the expenditure of energy necessary to accomplish a given task. Energy expenditure is a much easier concept to deal with than detailed analysis of forces as in the Newtonian approach. Body language signals clearly whether someone is working hard or not. Even without the benefit of biomechanics, everyone has an intuitive feeling that jerky, harsh movements with visible tension are not efficient. The ATS Skiing Model captures this distinction in the descriptions of what makes a movement efficient by using terms such as “flowing,” “smooth,” “guiding,” “continuous flow,” and so on.

This view is supported by the current thoughts in biomechanics research. A decade ago, very little was being done regarding the study of energy involved in human movement. Now, the focus is on the “human motors” themselves as generators, absorbers, and managers of energy. The sources of energy that need to be managed in the context of skiing are the energy derived from gravity (energy given to us by the lifts that raise us in the gravitational field), the energy available in our bodies (metabolism), and the energy available in skiing equipment as a result of deformation of the materials. We also need to manage our kinetic energy (a measure of our speed, a concept to be defined in the sequel). If we are racing, we wish to maximize the average speed over the course, if we are afraid of speed in recreational skiing, we wish to keep it reasonable. We can judge quality of motion by how well we manage the energy available to us in accomplishing our skiing goals, whether these are minimum time in a race or maximum enjoyment from a full day on the mountain. Recreational skiing, like any other motion sport, is enjoyable partly because of the sensation of speed and the control of motion. Smooth, seemingly effortless movements seem to give the most satisfaction.

What are the causes of inefficient movements? To understand muscular efficiency, we need to study the appropriate anatomy and physiology: how muscles work in relationship to the skeletal system and in reaction to external forces. Here I will comment on some of these efficiency issues. The most obvious is when extensors (the muscles that straighten body parts) and flexors (the muscles that cause contraction) are both firing. This is known as co-contraction in the biomechanics field. The muscles are, essentially, fighting each other to produce some net movement, resulting in a high expenditure of energy. This type of activity occurs most often when an individual feels the need to stabilize the body while performing some movement. This is felt as tension in different body segments during a run. To feel how this enters your own skiing, focus on how much relaxation you can achieve between turns or focus on which muscles are working during a particular turn. Note the difference as you move from the groomed snow to garbage to bumps.

Another cause of inefficiency is isometric contraction against the force of gravity. (An isometric contraction exists when a muscle contracts but no change of length takes place). In ATS, this cause is addressed through stance and the way the body's center of mass (CM) moves during turns. (The center of mass of the human body is not a fixed point but moves around as the body assumes different configurations, i.e. flexes or extends, or the limbs are moved etc.) While the term "stance" usually implies a static position, in skiing the body is rarely completely at rest. The term "stance" is used in ATS to describe the reference or neutral position from which movements are initiated or to which a skier returns after execution of a particular sequence of movements. The preferred mechanism for reacting to gravity (as well as other forces that arise during skiing) is to use skeletal alignment and not the muscles. However, because of the basic structure of the human body, it is impossible to achieve perfect skeletal alignment to bear the loads, unlike some birds and animals. For humans, some muscles are always working. The issue is to align the body in such a way that the efficiency is maximized. A somewhat more subtle point is that anytime a limb is held in a stationary position during motion, muscles may be reacting against the force of gravity in addition to whatever else is going on.

An additional cause of inefficiency, closely related to co-contraction, occurs when the energy generated at one joint is absorbed at another. This is a bit difficult to visualize, but often happens during alternating limb movements. For example, this occurs in normal walking during the double support phase when the energy increase of the push-off leg takes place at the same time that the weight-accepting leg absorbs energy. It is obvious that this type of activity needs to happen—the basic mechanics of the bipedal walking task require such movements—however, the efficiency of the event is determined by just how the movement is executed. An individual should expend no more energy on such necessary tasks than is absolutely necessary for the movement.

The last major cause of inefficiency in movement is the relative smoothness or jerkiness of the movement. Smooth movement is characterized by continuous interchanges of limb energy. Jerky movements consist of a succession of stops and starts. Each of these bursts of energy generation and absorption has a metabolic cost; therefore, jerky movements are inefficient.

Another area where energy considerations are helpful is in the analysis of turns, specifically the efficiency and effectiveness of turns. Instructors spend a lot of time discussing turn shape and how different movements influence turn shape. However, the real issues are: "What is the purpose of the turn or series of turns?" and "What are the means of attaining that purpose?" Simply put, the *primary* purpose of any turn is to change the direction of travel of the skier down the mountain - the guidance problem. The change in direction may also serve to reduce speed if speed control is one of the goals. To satisfy the primary purpose, any movement that results in the desired change of direction is correct. However, particular qualities are usually demanded, and these can radically change the mechanics involved. Everything from racing to recreational skiing in any conditions is included in an examination of the effectiveness and efficiency of turns. I remark in passing that a turn is initiated (a turn starts) when the external forces that change the direction of travel start to act. A turn is finished when these forces no longer act.

To understand how to judge the efficiency of ski turns, the concepts of mechanical work and energy must be considered. I will address these issues in more detail in the section dealing with work and energy, section V). For the purposes here, one can think of speed as a direct measure of kinetic energy. In essence, efficiency is an energy management game. For example, if you want to be the fastest down the race course, you need to be careful of how and where your kinetic energy is lost. The recreational skier may wish to use the turns to slow down, so where and how the kinetic energy is lost will also be of interest in that case. The ATS skiing model focuses on the concept of continuous flow of movement. This concept is directly tied to where in the turns you scrub speed and what the results are on the movement of your center of mass. If the changes are not smooth, then it is likely your body reactions will not be smooth either. And, as mentioned before, jerky movements are inefficient.

When applying the methods of energy analysis to skiing we rely on the work-energy relationship: The change in the kinetic energy of a skier, which is a measure of the skier's speed, is equal to the work done by the external forces acting. Work, in the technical sense that I need here, is defined as the product of the component of force along the path on which the body moves times the path length. Thus, a force that always acts perpendicular to the path (at right angles) does no work and cannot change the speed of the moving body. It does change the direction you are moving (your velocity) but not the speed (the magnitude of the velocity). A detailed discussion of these issues is given in chapter 5.

Thus, one can argue that the pure carved turn on one ski will be the fastest way to make a turn while remaining in contact with the snow. The easiest way to visualize (and define) the pure carved turn is to think of the ski edge leaving a sharp clean line in the snow. We often see this in carved snowboard turns; it is less obvious in alpine skiing. This type of turn will be the fastest (lose the least energy) because the turning forces on the ski always act at right angles to the path thus doing no work. The only loss is due to the friction forces acting along the ski edge and bottom. To answer whether a carved turn on one ski or two results in the least energy loss is a bit tricky since the total frictional forces acting will depend on many factors. Among these are 1) the normal (at right angles to the ski base) pressure exerted on the snow, 2) speed, 3) the surface area of contact between the snow and the ski(s), 4) the structural properties of the snow (density, water content, crystal structure etc.) and 5) how far the ski(s) penetrate the snow surface. I will have more to say on the friction issue in the section dealing with the nature of forces (section 3.6.4). The choice of whether to make the turn on one ski or two is usually determined by the amount of side forces that are required by the turn and the speed at which the skier is traveling. On hard snow, we need penetration of the snow surface, so we need the maximal pressure, i.e., force divided by the area over which the force acts. If you use half the area (one edge), you will get twice the pressure and thus greater surface penetration. However, the amount of side force that the snow is able to generate depends on the shear properties of the snow. (Loosely speaking, the shear force is the resistance of the surface to being scraped by a sharp edge.) The exact nature of what the interaction forces between the ski and the snow are is a complicated matter. For more on this topic, see section 3.6.4.

If the objective is to minimize the loss of speed, then the conclusion is that the pure carved turn is the most efficient turn. For the conclusion to always hold, however, the underlying premises must continue to be true. The key premise is that the ski slices or "carves" through the snow in a nice arc with no lateral displacement or travel in the lateral direction whatsoever. That is, if we draw the arc of the desired turn on the snow, the ski bends just so and every point of the ski edge passes over every point of the drawn arc.

Unfortunately, this set of circumstances, necessary for the pure carved turn to happen, are very difficult to obtain in real skiing situations on a consistent basis. Snow is an uneven surface with varying consistency throughout the race course or ski run, the ski does not like to remain appropriately bent. The technical ability and the muscular strength and sensitivity of the skier to cope with the magnitudes and changes of the forces involved may be lacking. As a consequence, pure carving is usually attained only occasionally for most skiers and the major part of a given turn is characterized by slipping, skidding, chattering or other not-so-elegant phenomena. And since the skis are now traveling with the long axis at an angle to the intended arc of the path, the forces that are turning the skis are also doing work. So speed is lost. Even so, "somewhat" carved turns may be preferable in most situations and seem to afford the best efficiency and enjoyment to skiers. It is worth noting that the pure carved turn is more evident in snowboarding than in skiing. This is the result of significant differences in the mechanical response of a snowboard to loads as compared to the response of skis due to fundamental differences in structural properties. Another contributing factor is the fact that on a snowboard, we always work with a single edge and the body is more favorably oriented on the board for load transfer to the edge than it is on skis.

The key issues in determining *how much* speed is lost are: 1) How well aligned to the intended path do the long axes of the skis remain *throughout* the turn, and 2) how large is the (resultant) across-track component of the ski/snow interaction force? The issue of ski alignment is obvious if the ski is slipping or skidding across the snow. Perhaps not so obvious is the case where the ski chatters or displaces laterally (parallel to the intended path) *without* achieving an apparent angle between the long axis of the skis and the path. In this case, each time the ski hits the snow (chatters), we have a relatively large impulse perpendicular to the ski acting over a short distance and this will do work (the ski does move laterally upon contact with the snow). The easiest way to recognize this effect is to relate it to the slowing down that you experience in straight running every time your ski tips hit some loose snow or terrain irregularities. Again, see chapter 5 for more discussion of these issues.

When analyzing specific situations, an easy way to keep track of the path is to follow the boots. Recall that what really contributes to the loss of speed is the *total* work done by the forces and therefore a large force acting over a small distance will give you the same amount of work (and thus loss of speed) as a small force acting over a large distance. So if you decide to carve, and for various reasons are unable to *maintain* the carve, the work done by the ski/snow forces during the (relatively short) loss of carve phase may still be larger than if you had elected to use a light, skidding turn over the entire distance, perhaps the entire turn. If the ideal carve can be maintained throughout the turn, no problem. If not, a great loss of speed is possible. Thus in some situations in the race course it may be unwise to strive for a carved turn that you may be unable to carry out successfully for the entire turn. The typical situation where the skier is able to maintain a clean carve is in turns that do not demand high lateral forces. An example of a situation where the skier is not able to maintain carving is when he or she is making very short turns or turns on a steep segment of the slope. Loss of the carve usually occurs just when the lateral forces are the greatest, for example, at the finish part of the turn or on the steepest part of the hill. As I noted earlier, the skier's skill, strength, sensitivity and judgment are all involved in defining the best strategy.

The ski run is an energy management game. You do not have many opportunities to increase your speed, but you have countless opportunities to lose speed. Remember that the major source of energy is just what you get from gravity (the pull of gravity accelerates you thus increasing your kinetic energy). What needs to be emphasized is that not all losses are equivalent, even though the speed loss is numerically the same, as there are hidden costs as well. Two such sources of hidden costs are worth recognizing here. First, not all parts of the course or run are created equal. As everyone knows, loss of speed on the flats costs you more than an equivalent loss on the steeps, simply because gravity cannot accelerate you as quickly, even when aided by muscular forces through skating or poling actions. Second, the greater your speed at any point, the greater the force required to change your direction by a given amount. This means that if you arrive at a gate with greater speed than the next racer, but the *direction* you are going is wrong for where you need to go next, you may need a larger force on your skis to get the necessary change of direction. As a result, you run a greater risk of having the skis travel sideways - lose carving, scrub energy, slow down - and thus be worse off than if you had arrived traveling slower on a better line.

Each specific situation will dictate what the correct strategy should be for each individual. You must know your own strength and technical skills to make the judgment. An intimate understanding of how your skis and boots perform under various speeds is also critical to maximizing speed through a given turn. The primary focus as you play around with carved turns should be on what happens when the turn *doesn't* work. When do you break away, in what fashion, what was the turn like in terms of sharpness, entry and exit? The objective is to develop a physical feeling of what is going on. Use the knowledge of what is happening underfoot to guide explorations of the physical situation. If you are so inclined, a study of the underlying mechanics and biomechanics will increase your understanding of why certain things happen.

2.4 MOVEMENT ASSESSMENT

The ultimate goal of a ski lesson is to create effective and efficient movement patterns for the skier to use in all conditions. So in a sense we are *synthesizing* movements. The first step in implementing a program to improve motor skills, be it instructor facilitated or self-learning based, is to assess the present movement patterns, effectiveness and efficiency. As an instructor, you will be spending considerable time doing movement assessment of the student. Based on your observations you then develop a suitable lesson plan with the objective of building new movement patterns. Therefore, a better term in most cases is movement assessment, rather than movement analysis, to focus on the constructive aspect of ski instruction. Movement analysis is what one does to determine exactly what is going on in a particular movement to determine such things as cause and effect, relationship of limbs during the movements and so on. Such analysis requires considerably more time than is usually available on the hill.

A significant part of certification examinations involves movement assessment as well. Often this topic will arise in the context of "error recognition'" or "error correction." Since ATS promotes a non-judgmental, humanistic, teaching/learning environment, the focus is better placed on "movement assessment." "Error'" is not a non-judgmental term. Similar considerations hold for discussions of "bad habits." If a student has never had a lesson but has experimented with skiing alone (or been instructed by well meaning but nonprofessional friends), he or she will have developed many ineffective or inefficient movements. Your task as a teacher is to show the student there is a better way without attaching a negative judgment to what he or she already knows. Also, as observed earlier, conscious movement assessment and analysis of your own performance is necessary for a true understanding of skiing.

Trained physical educators study kinesiology (the study of muscles and their movements) to better understand the elements of physical performance and to be able to teach motor sports. One of the best texts in this area is *Kinesiology* by Logan and McKinney (Brown Co. Publ., 1972). A key point they make is that "Teaching neuromuscular skills is based on 1) the analytical ability of the physical educator and 2) the ability to communicate pertinent facts of skill analyses to learners. Analysis is the beginning point for teaching."

They also note that much of the analysis in teaching motor sports is done visually, after only a cursory (often one time) observation of the performance, with immediate feedback to the student. Experienced instructors know enough to restrain themselves from instant analysis and comments, but the inexperienced often engage in "instant teaching" because they feel they must *do* something or else the students may think no instruction is taking place. A valid analysis of what is causing difficulties in a given individual's skiing may require many runs and observations. Better yet, a video camera may be used so that specific movement patterns can be isolated and viewed repeatedly. Exercise caution in the use of video, however, as it may interfere with a student's learning. Video is an excellent means of self-analysis.

Even though much has been written in the physical education field since 1972, Logan and McKinney's suggested sequence for movement assessment and analysis still forms the basis for a practical and sound approach. They propose a segmental approach to observing sports skills in visual as well as cinematic analysis. Their suggested sequence for assessment is as follows: 1)The total performance, 2) pelvic area and the rib cage, 3) base of support or feet, 4) head and shoulders, 5) arms and hands, 6) knees and hips, 7) follow through, and 8) the total performance again. For skiing, follow through (the movement of the body or limbs after the release of a thrown object) is not an important feature. Furthermore, the preferred sequence of observation for skiing is: 1) The total performance, 2) pelvic area and the rib cage, 3) knees and hips, 4) base of support or feet, 5) head and shoulders, 6) arms and hands, and 7) the total performance again. Implicit in this of course is the awareness of what the skis did in the turn. The behavior of the skis is covered under point 4) above. Clearly, no one will be able to observe all of the above in one trial or even a few turns. However, when performing movement assessment, you need to have a clear purpose in mind—what you are trying to learn from the observations and analysis. You also need a clear plan for observation—how you are going to observe the performance.

The purpose of movement assessment can often be related to what the customer seeks from the lesson. For example, the goal may be to finally learn parallel and get rid of that annoying stem. In this case, the purpose of movement assessment is to determine why the customer is unable to ski parallel. There may be several reasons:

- strong one-two motion at turn initiation, inability to turn both feet and legs
- fore-aft balance problems
- insufficient flexion/extension movements throughout the turn
- inability to let the skis run (fear of speed)
- inability to commit the body motion downhill (fear of fall line)
- possible body alignment problems (under or over edged)
- equipment mismatch (skis too long, boots too stiff)
- uncertain lateral balance, inability to adjust support from one ski to the other to both

One additional point, when we discuss technical issues, such as precisely what information movement assessment provides and how we should use it, we need to keep the audience clearly in mind. The information needs of the instructor and the student are clearly different. Unless asked, keep the discussion simple for students. For instructors, be certain of your understanding before starting a technical discussion. Remember that for students your goals should be to improve their effectiveness and efficiency and their understanding of what the movement options are in different situations. The following material is best reserved for indoor contemplation and discussion. When you go skiing, leave the texts and manuals at home!

With this survey of the technical basis for ATS, I can move on to an in-depth discussion of mechanics, anatomy and physiology.

3. THE VOCABULARY AND CONCEPTS OF MECHANICS

3.1 A BRIEF HISTORY

The study of dynamics - how bodies move - is one of the oldest branches of science. Although it would be presumptuous to assign an "official starting date" to dynamics research, it is generally agreed that the work of Galileo Galilei (1564 - 1642) first put the subject on a sound footing. Mixing observation with deduction, Galileo was the first to deal with the concept of acceleration and to establish the study of dynamics as a branch of natural philosophy. Then, Johannes Kepler's (1571 - 1630) efforts to understand and explain the motion of the planets gave the impetus to applied dynamics. Isaac Newton built on the foundations established by these pioneers and, through his insistence on clear, succinct explanations established what we now call "classical dynamics" with the publication of the *Principia*, July 5, 1686. In the process, Newton invented the calculus (even though some of the key concepts had been around since the time of Archimedes), one of the most significant accomplishments in the long and distinguished history of mathematics, the ultimate "shorthand" for precise language.

Concurrently, Gottfried Leibnitz (1646 - 1716) linked mathematics, dynamics and natural philosophy even closer. An independent co-inventor of calculus, Leibnitz also laid the foundations of combinatorial analysis, one of the most powerful tools in the modern world of discrete mathematics (the basis for all modern computers). Then, Leonhard Euler (1707 - 1783) established as sound a basis for analyzing the dynamics of bodies of finite size as Newton had done for particles. As we shall see, it is the problem of how bodies of finite size move that really is of concern in analyzing human movements and that dependence only on the fundamental results of Newton can be very misleading.

Finally, I wish to note the contributions of Joseph-Louis Lagrange (1736 - 1813). Lagrange was the father of what today is known as the Lagrangian approach to dynamics, even though, as with many events in the history of this fascinating subject, the roots were well-established by others. Lagrange was one of the first to depart from the tradition of using observation, experiment and analysis in concert to reason about dynamics. "No diagrams will be found in this work" Lagrange says in the preface to his masterpiece, *Analytical Mechanics*. For those who are familiar with the nuances of mathematical modeling, it is known that if the forces of reaction in a system of interacting bodies are not of explicit interest, the Lagrangian approach offers many advantages, not directly available in the methods of Newton. Not surprisingly, there are now numerous symbolic algebra computer programs available that allow one to derive the mathematical equations of motion for very complex systems by letting the computer do all the algebra. These programs are based on the concepts of Lagrangian dynamics. We close this brief look at the founders of dynamics with a phrase that Lagrange was not afraid to use: "I do not know." Too often we are unwilling to admit that we "do not know," an admission that is the necessary first step to learning. In the study of human motion, we encounter such complexity that often the only answer is: “I don’t understand what is going on”. This should be motivation for exploration and perhaps understanding can be increased. But to do so, one needs to understand the basic concepts that can be applied to reason about motion.

3.2 THE FUNDAMENTAL LAWS OF MOTION

The fundamental Newtonian laws of motion govern all that we do on skis or any time we move, for that matter. These laws have undergone many restatements over the years as the language of mechanics has become modernized. For my purposes, however, the original form is a good place to start (from *Principia Vol I. The Motion of Bodies,* Sir Isaac Newton, Motte's Translation, revised by Cajori, University of California Press). After all, Lagrange once observed: "Newton was assuredly the man of genius *par excellence,* but we must agree that he was also the luckiest: one finds only once the system of the world to be established."

Because the original wording of the laws is not necessarily easy to relate to everyday experience, I will restate them in modern form immediately following the original versions. One caution: as originally formulated by Newton, the laws apply to *particles,* that is, bodies whose physical dimensions can be considered to be so small that their dimensions can be neglected in comparison to the scale of the motions that we are interested in. This of course was the focus for Newton, who was interested primarily in the motion of the planets. So when you read "body" in Newton's definitions you must realize that he meant "particle." Later on, Euler extended the laws to apply to situations where one could not neglect the physical shapes and dimensions of the bodies. I will discuss the implications of this situation later.

A suggestion here: Read the statement of these laws again after you have read the sections defining the words used and again after reading the sections on interpretation of the laws.

LAW I

Every body continues in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed upon it.

LAW II

The change of motion is proportional to the motive force impressed; and is made in the direction of the right line in which that force is impressed.

LAW III

To every action there is always opposed an equal reaction; or, the mutual actions of two bodies upon each other are always equal, and directed to contrary parts.

To these Laws, we need to add Newton's first corollary (often called the fourth law, the parallelogram law of forces):

COROLLARY

A body, acted on by two forces simultaneously, will describe the diagonal of a parallelogram in the same time as it would describe the sides by those forces separately.

These then are the basic laws that we will strive to understand and apply to the analysis of human motion on skis. In more modern language, these laws are:

Law I

A particle remains at rest or continues to move in a straight line with constant velocity if there are no unbalanced (motive) forces acting on it.

Law II

If an unbalanced (motive) force acts on a particle, the particle will accelerate in the direction of the force.

Law III

The forces of action and reaction between interacting particles are equal in magnitude and opposite in direction.

Corollary

Forces add as vectors.

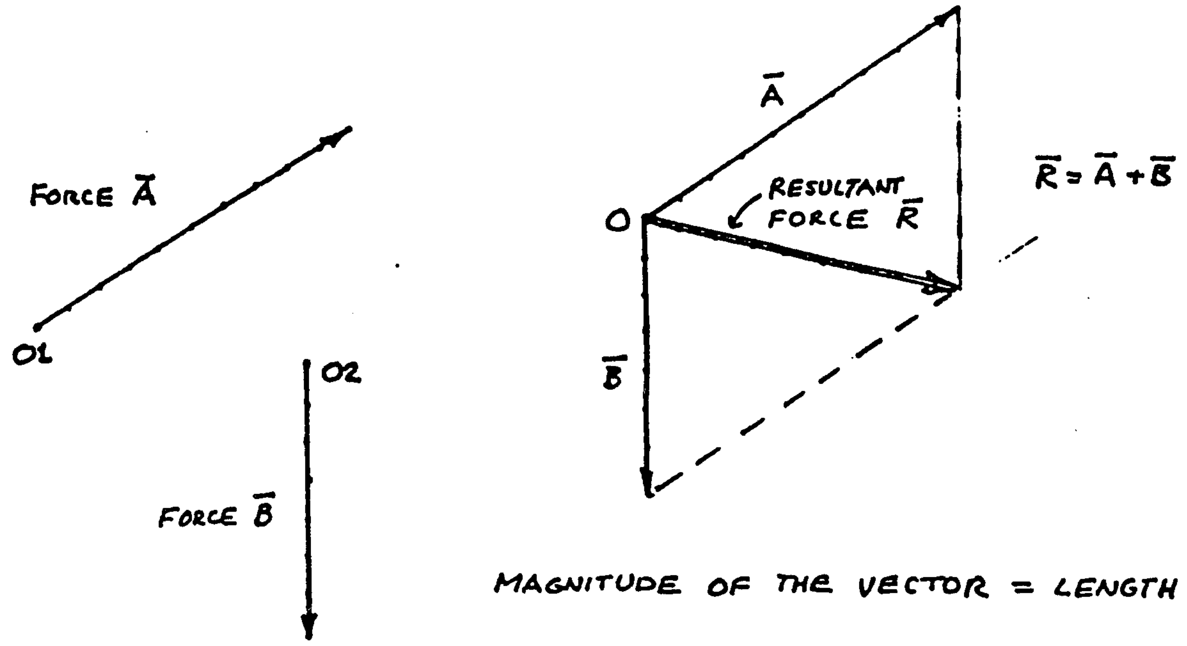
We are only concerned with the resultant of a system of forces acting. Figure 3.1 illustrates the concept of a vector quantity. The meaning of the corollary ("the parallelogram law") is shown for two vectors, but applies to any number: we can start with any two, add them, then take the resultant and add another and so on. The converse is also shown on Figure 3.1. That is, given any vector we can break it down into as many component vectors as we like. For example, the force of gravity which acts toward the center of the earth can be broken down into components parallel and perpendicular to the slope. Another point worth noting is that for the addition of vectors, we can move the point of application (the starting point of the arrow) to anywhere we like provided that we keep the length of the vectors the same and move them so that the new and old lines of action remain parallel. A word of caution here, though. When dealing with forces and their effects on bodies, we need to be careful since in general, when the point of application of the force is moved, we must also introduce an equivalent moment. This issue is discussed in detail in chapter 4.

I have retained the concept of a "motive" force in these restatements of Newton's laws since it accurately captures the fact that a force is not required to keep a particle (or a finite body) in motion once it has been set in motion. *The effect of a force is to change the velocity, not maintain it!* The use of the phrase "unbalanced force" captures the essence of the corrollary or so-called fourth law: The vector nature of forces and the rules for evaluating the net result of a system of forces that are acting determine the effect of the forces. This concept will become clearer in the sequel when I illustrate what this means.

These laws can be restated in the language of mathematics - the mathematics that Newton had to invent in order to efficiently work the various problems that occupied his attention. This restatement is found in appendix II. Here I will examine the key concepts from a more fundamental point of view. These concepts are the following: Frames of reference, mass (Newton's "quantity of matter"), motive force, states of rest and uniform motion (the concept of inertia), momentum (Newton's "quantity of motion"), change of motion (modern "time rate of change of momentum"), action and reaction, vectorial nature of forces and motion, and the meaning of the parallelogram of forces (the concept of resultants of force systems).

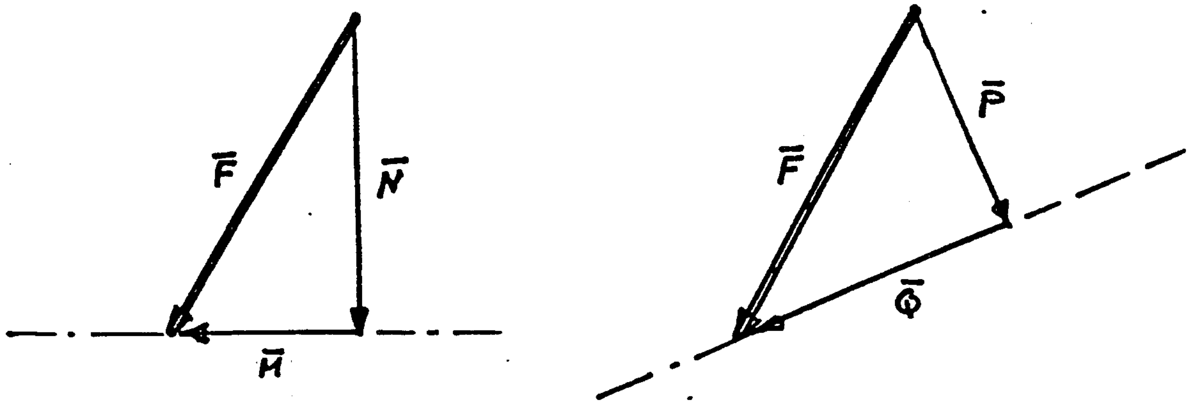
3.3 REFERENCE FRAMES AND SPECIFICATION OF LOCATION

The first concept we need is the concept of a *frame of reference*. The laws of motion imply the existence of a reference frame with respect to which we may determine whether a body is at rest, or in uniform motion, or undergoing a change in motion and in



MAGNITUDE OF THE VECTOR = LENGTH

ADDITION OF FORCES (PARALLELOGRAM LAW)
NOTE TRANSFER OF POINT OF APPLICATION OF
FORCES $\bar{A}$ AND $\bar{B}$: O1 TO O, O2 TO O.



EXPRESSING A FORCE $\bar{F}$ IN COMPONENT FORM

FIGURE 3.1 FORCE VECTORS

what direction that change takes place. In modern terminology, the underlying assumption is that there exists something called an *inertial frame of reference*, a reference frame that is absolutely at rest. The questions of the existence of such a frame and what one means by "absolutely at rest" are of significance when analyzing the motion of spacecraft. For the analysis of skiing, the earth provides the necessary frame. That is, we can think of the top of the lift from which we just unloaded or a tree at the top of the run as the point relative to which we will define the position and velocity of the skier.

The position relative to this reference point is a vector quantity. A vector quantity has both a magnitude (how many feet or meters are we away from the reference point when measured in a straight line) and a direction (in what direction with respect to the lift or tree are we located). Because this position vector is defined relative to a point fixed to the earth, it is an *inertial position* vector (remember that for our purposes the earth is a suitable inertial reference frame). The state of *rest* thus is defined as one for which the inertial position vector does not change in time. Its magnitude neither increases nor decreases, nor does the direction of the vector change. *Uniform motion* is defined as motion for which the particle moves at constant speed in a straight line with respect to the inertial reference frame. This condition is experienced every day when you drive your car in a straight line at a constant speed. A car moving at 55 miles per hour on a straight stretch of the interstate is in a state of uniform motion.

3.4 MASS

We can use Newton's own definition of mass, or the quantity of matter.

"*The quantity of matter is the measure of the same, arising from its density and bulk conjointly*".

In modern terminology, mass is the property of a body defined by its density and volume. It is a constant quantity (of course, over time it does change in response to our exercise and dietary habits!). The mass is proportional to weight and that is usually the means we use to measure it. We measure the body weight (pounds force) and divide the weight by the constant gravitational acceleration of the earth, $g = 32.174$ ft/sec^2 (or $g = 9.81$ m/ sec^2) to get the mass.

3.5 INERTIA

Associated with the states of rest or uniform motion is the concept of *inertia.* Newton introduced this concept as "vis insita", or *innate force of matter.* He observed that: "A body, from the inert nature of matter, is not without difficulty put out of its state of rest or motion" and thus one could use the term "vis inertiae" (the *force of inactivity*) to describe this tendency. One must be careful though, in the use of the term "force" in this context so as not to confuse inertia with acting forces. Newton avoided this confusion in that he used the term "motive forces" to describe forces arising from sources external to the body whose motion he was studying. Again, since mass is proportional to weight, we know from numerous experiences of trying to move heavy objects that more force is required to get the heavier ones moving, and that once they are moving, more force is required to stop them from moving.

A modern definition of inertia then is:

The resistance of a body to a change of magnitude or direction of its velocity.

Alternatively, one can substitute "motion" for "velocity" and think of inertia as the property of a body that resists changes in its motion. The larger the inertia, the more motive force it takes to change the motion.

3.6 FORCES

The concept of *motive forces* is key to understanding the cause and effect relationships inherent in Newton's laws of motion. Motive forces are the only forces capable of changing the state of motion of a body. We will need to distinguish between *external motive forces* and internal forces, as we will have to consider the finite dimensions of the human body in analyzing skiing mechanics as well as the fact that the body can generate forces internal to itself.

For the purposes of understanding the mechanics of skiing, the only external motive forces are:

- gravity, a constant force in both magnitude and direction, uncontrollable
- interactions between the snow and the skis, highly variable and controllable
- interactions between the poles and the snow, highly variable and controllable
- air resistance to the motion of the skier's body, skis, poles (air drag), somewhat controllable

That is all! Some of you are already asking: But what about centripetal force? Centrifugal force? Aren't these also forces? Well, yes and no.

3.6.1 CENTRIPETAL FORCE

First I will tackle the concept of centripetal force. The prominent position this concept has occupied in discussions of dynamics can again be laid at the feet of Newton. His definition:

"A centripetal force is that by which bodies are drawn or impelled, or any way tend, towards a point as to a centre".

He then follows this with: "Of this sort is gravity, by which bodies tend to the centre of the earth; magnetism, by which iron tends to the loadstone... A stone, whirled about in a sling, endeavors to recede from the hand that turns it ... the force which opposes itself to this endeavor, and by which the sling continually draws back the stone towards the hand ...because it is directed to the hand as the centre of the orbit, I call the centripetal force." This designation and the role that the concept of centripetal force then plays in Newton's development of mechanics was again motivated by his interest in the motion of the planets.

However, the real physics of the situation is more accurately described if we think of gravity as gravity, not centripetal force, magnetic force and not centripetal force, and tension in the string, not centripetal force. In skiing, what is most often described as a centripetal force is the component of the ski/snow interaction force acting towards the instantaneous center of a turn. For clarity of thinking, it is best that we view the term *centripetal force* as descriptive, in the same fashion that Newton originally introduced it in his definition. **The ski/snow interaction forces are something we can feel and are clearly identifiable, so we have no need for *centripetal force*. You might argue that**

the term contributes something. Maybe so, but the potential for confusion arises when talking of the centripetal force *and* the ski/snow interactions as two separate entities, when in fact they are one and the same!

3.6.2 CENTRIFUGAL FORCE

What about centrifugal force? Well, this is quite a bit more tricky and I will postpone the discussion of this until we have a chance to look at the content of the laws of motion more closely (see the section on the interpretation of the Second Law, section 3.10.2) and appendix II). Bear with me.

3.6.3 THE NATURE OF FORCE

As I have noted, we need to distinguish between external and internal forces when thinking about the mechanics of skiing. The internal forces we contend with are those due to the action of muscles and the interactions of bones, cartilage and ligaments. These we will discuss later as part of the discussion of anatomy and physiology.

Let me now return for the moment and reflect on the nature of force with the understanding that we are interested only in the external motive forces that may act in skiing situations. Force is intuitively understood by most people as a push or a pull one can exert with one's body. This is in agreement with Sommerfeld's observation that (Arthur Sommerfeld, *Mechanics, Vol I. Lectures on Theoretical Physics,* Academic Press): "The same is true for the concept of force as for all physical concepts and names: word definitions have very little meaning; physically significant definitions are obtained as soon as we prescribe a way of measuring the quantity in question." For example, we can measure an arbitrary force by balancing its effect by a suitable weight, that is, by comparison of the given force against a standard of gravity by suitable "weights."

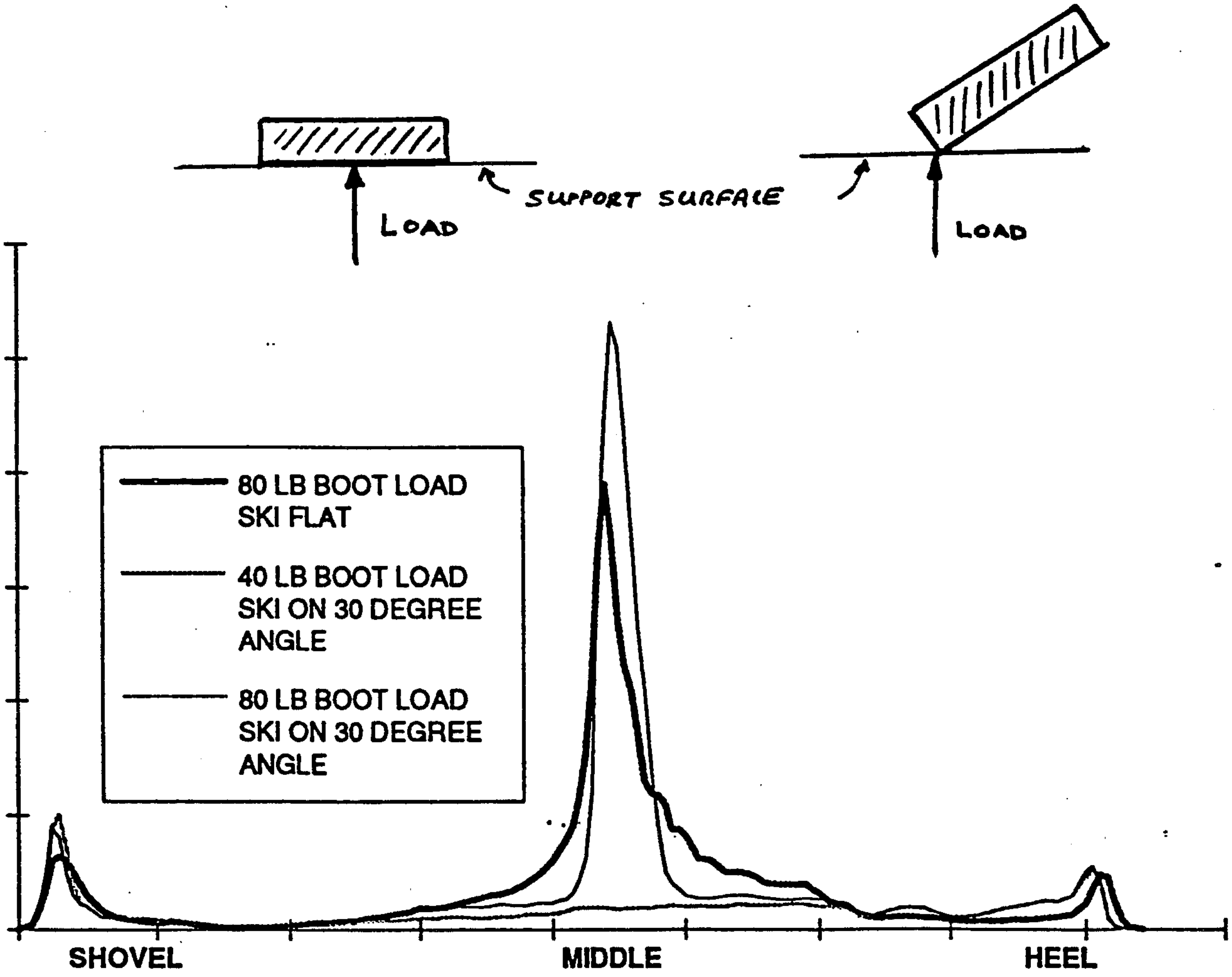
This is certainly true of the forces involved in skiing. We experience a measure of force through the mechanisms of how our bodies react to the force. We can resist (balance the effect of) air drag by increasing the tension in the muscles of our bodies, the action of the snow on our skis by the tension of the muscles in our legs and torso, the pressure of the snow on the pole by the tension in our arm and shoulder and so forth. This understanding of force as a result of sensing something in our bodies will play a key role in unraveling the mysteries of "centrifugal force" and whether it is real or fictional as some may claim.

3.6.4 SKI -SNOW INTERACTION FORCES

We need to gain an understanding of the nature of ski/snow interaction forces. These are in general very complex. For this reason the following discussion is quite technical! For the purposes of analyzing skiing, I will consider the different ways that the skis interact with the snow: 1) The normal pressure to the bottom surface of the skis, 2) the sliding resistance or friction, and 3) the reaction to the edges as they scrape across the snow surface (skidding resistance). These forces are distributed forces as illustrated on Figure 3.2 and usually have a rather complicated form. To deal with them we usually replace the distributed force fields with equivalent resultant forces acting at the appropriate location on the ski. I will return to the issue of what the appropriate location is and why the point of action for the resultant is important in chapter 4.

The normal reaction to the base of the skis is conceptually the simplest. The term "normal" in technical use means "perpendicular to the surface". From the Third Law we know that this force must be equal and opposite to the total normal force impressed on

NOTE: The force distributions shown in this Figure are measured with respect to the horizontal surface on which the ski rests. For the "ski flat" case, the load is normal to the ski and the surface, for the 30 degree angle, the load is normal to the surface but represents the ski edge load as indicated in the sketch.



(Data courtesy of the K2 Corporation)

FIGURE 3.2 EXAMPLE OF FORCE DISTRIBUTION ON A SKI the skis. This total normal force will be the combined result of gravity and the effects of motion, such as "weighting" or "unweighting" movements as well as turning (the mass times acceleration part of dynamics). The only complication that arises is due to the effects of snow compressibility. The snow will compress under the action of the impressed forces upon it until it is able to resist them, similar to the action of your bed springs that deform until they are able to resist your body weight as you lie on the bed.

I wish to make some comments here about the terms "weighting" and "unweighting". These terms are entrenched in ski instructor jargon, and often create confusion in the same way that "centripetal force" does. I will address this issue in more depth in the section dealing with misconceptions about mechanics (chapter 6), however, I remark here that "weighting" and "unweighting" describe the changes in the normal pressure forces that the skis experience as a result of the body accelerating up or down and the forces that must exist to create a change in the direction the body is moving i.e. up or down.

The sliding resistance - friction - is quite a bit more complicated. There are no basic physical laws from which one can deduce the correct description of the force of friction. For all engineering applications, models for friction forces are determined experimentally. The usual approach is to devise some tests, postulate a friction model based on the test results and the required parameters for the model are then estimated from the data. Two common friction models are "Coulomb friction" and "viscous friction". Coulomb friction models describe what happens between two dry surfaces. Viscous friction models describe what happens if there is a lubricant or fluid film between the two surfaces. There are of course situations that are some combination of the two. For example, the fluid layer is not as thick as the height of the irregularities on the surface and one has solid to solid surface contact in some areas while in other areas the surfaces are separated by the fluid.

Dry surface friction exhibits two different behaviors. First, there is static frictional force (so-called "stiction").This is the force resisting motion when there is no slipping. Its value varies as the need to prevent motion is developed, reaching a limiting value, when slipping starts. The value of the coefficient of static friction is the ratio of the normal and tangential forces at the instant that slipping starts and depends on the materials of the two surfaces. Second, there is the kinetic frictional force (Coulomb friction). This force opposes motion, once slipping starts, and is usually less than the limiting friction force that prevents motion from starting in the first place. The empirical law for Coulomb friction is that the friction force is directly proportional to the pressure between the two bodies and the coefficient of proportionality is independent of the value of the pressure. This means that the *friction coefficient* for a light skier and a heavy skier is the same for the same surfaces, but not the total frictional force. The coefficient of friction is also independent of how fast the two surfaces are slipping relative to one another as well as the area of contact. Remember that these are only approximations to what happens and are valid for dry surfaces, an assumption that is not necessarily true for the ski - snow interface.

Viscous friction models on the other hand assume that the friction force is proportional to the relative speed of the two surfaces that are moving in relation to one another and is directed in opposition to the direction of motion. These models are usually used when there exists some form of a fluid between the two solid surfaces as is the case with automotive lubricants. In many instances, this is also true for the ski - snow interface. The pressure on the snow causes local melting of the snow crystals, so we are really skiing on a thin layer of water. You can often see visual evidence of this phenomenon when examining the ski tracks which show a glazed appearance relative to the surrounding snow. There is a difference between so called thin film lubrication (fluid layer thinner than the height of surface irregularities) and thick film lubrication, when the film thickness is large compared to the irregularities. The thick film case is the easier of the two and probably the most relevant to skiing. The complexity of what happens at the base/snow interface can be readily appreciated from the intricate tuning and wax preparation required for maximizing gliding. Base structure is clearly related to issues of thin and thick film lubrication.

In the case of thick film viscous friction, Newton observed that the force opposing motion is directly proportional to the area and the relative speed and inversely proportional to the thickness of the lubricating film. That is, the force resisting motion is larger for larger speeds and contact areas and lower for thicker films. As long as there is no direct contact between the two surfaces (the thick film assumption), the resisting friction force is independent of the pressure, that is, the normal force between the surfaces. Thus a light skier and a heavy skier on the same area skis moving at the same speed will have the same friction force resisting their motion, provided that the melted snow layer for both is the same. Of course, this last assumption is questionable, since whether or not the snow under the skis melts does depend on the pressure applied and the heavier skier will exert more pressure. The interested reader who wishes to learn more about the nature of sliding friction and boundary lubrication of snow can consult the paper by Glenne [Glenne, 1987] or Colbeck [1992].

Last but not least, we have the forces that arise when the ski edges move over the snow surface in a scraping fashion or what we could call skidding. (We can call these "shear" forces consistent with the use in the field of solid mechanics). The best way to understand these forces is to think about what the forces are when scraping the fresh wax job on your skis. As anyone who has tuned and waxed skis knows, the force required to scrape off the wax will depend on the properties of the wax, the sharpness of the scraper, the angle at which the scraper is held against the ski surface and the downward pressure exerted on the scraper. All real ski turns involve some shear forces. These are the forces that cause the snow to spray from the edges of skis in a turn. These shear forces are not friction, by the way. The ability of the snow surface to resist shearing forces will greatly influence the degree of carving we can achieve. Remember that a pure carved turn implies that every point of the ski passes over the same point in the snow, which in turn must not be displaced. Ice has the greatest resistance to shearing. So, provided that the skier is strong enough and skilled enough, a pure carved turn is easiest on ice. As the surface becomes softer, the ski edge can penetrate deeper and the shearing action starts to couple with the normal reaction of the snow (to the base of the ski). From this discussion it is apparent that what goes on at the ski - snow interface is really very complicated.

All forces are also by their very nature vectorial: They have a magnitude (how hard you have to push or pull) and a direction (in which direction do you have to push or pull). The vector nature of forces will allow us to simplify some fairly complicated situations later on since usually several forces act at the same time.

3.7 ADDITION OF FORCES

The vector nature of forces thus brings us to the parallelogram of forces (Newton's corollary) or, how should we add up the effects of multiple forces. This is extremely significant because it allows us to use the *principle of superposition of forces*: The axiom that each force acting on a mass point contributes to its change in motion in the same way that it would if it were the only force acting. The parallelogram law also allows us to replace an entire system of external forces, whose origins might be quite different and which have different magnitudes and directions of action, with a single resultant force which has a single magnitude and direction of action. This concept was illustrated on Figure 3.1.

Note in these diagrams that if the individual forces act in just the right way, their resultant can be zero. In this situation one can speak of the forces as *balanced.* The concept of the balance of a system of forces is critical to understanding the meaning of the laws of motion and thus the mechanics of skiing. (I will also use the word "balance" in the ski specific context as well, the connection to how balance is used here will become evident then.)

3.8 MOMENTUM

The next concept is that of momentum, or what Newton called the "quantity of motion". Newton's definition was:

"The quantity of motion is the measure of the same, arising from the velocity and the quantity of matter conjointly".

In modern terminology, we see that the quantity of motion or momentum is defined as the product of the mass and the velocity of the body. Since velocity is a vector quantity, then momentum is as well. A body at rest has zero momentum, a body in motion has momentum. With the mass of a given body constant, we see that speed is a direct measure of the magnitude of the momentum and the direction of the velocity (vector) is the direction of the momentum vector.

Note that momentum and inertia are not synonymous. Inertia is a property of the body whether it is in motion or not and the mass of the body is a measure of its inertia. Momentum is non zero only if the velocity is non zero. The Second Law states that force and the time rate of change of momentum are the same, *not* that the terms momentum and force are interchangeable!

3.9 CHANGE OF MOTION

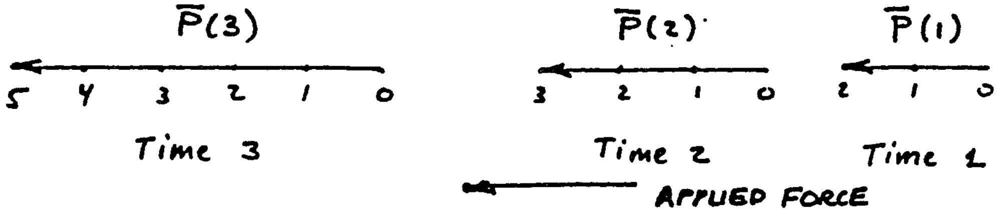
Change of motion thus is to be interpreted as the change of momentum over time. Since momentum is a vector quantity, this means that the momentum vector can change its magnitude, its direction or both. Since momentum is the product of mass and velocity and the mass is constant, then the change in momentum is equivalent to the change in velocity times the mass. The concept of the change in a vector quantity is illustrated on Figure 3.3 which shows the three ways that the momentum vector can change, depending on the nature of the applied force.

This completes my initial discussion of the basic concepts of mechanics. With this information, we can now examine the content of the basic three laws of motion.

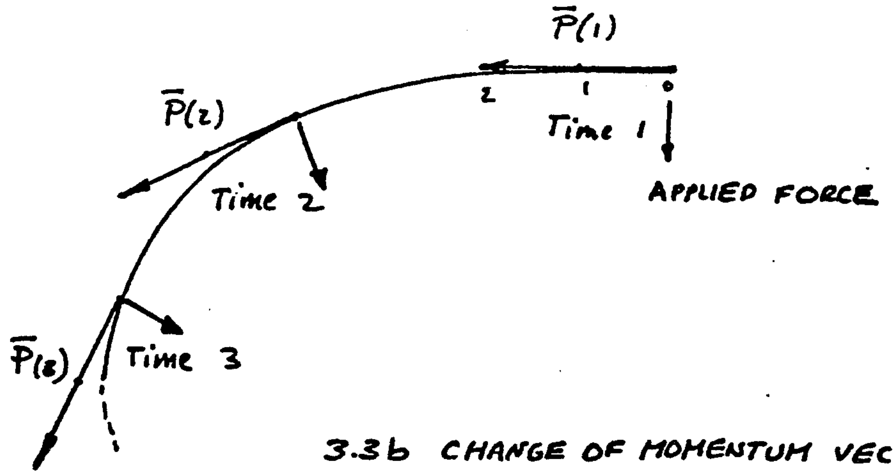
3.10 INTERPRETATION OF THE LAWS OF MOTION

3.10.1 THE FIRST LAW

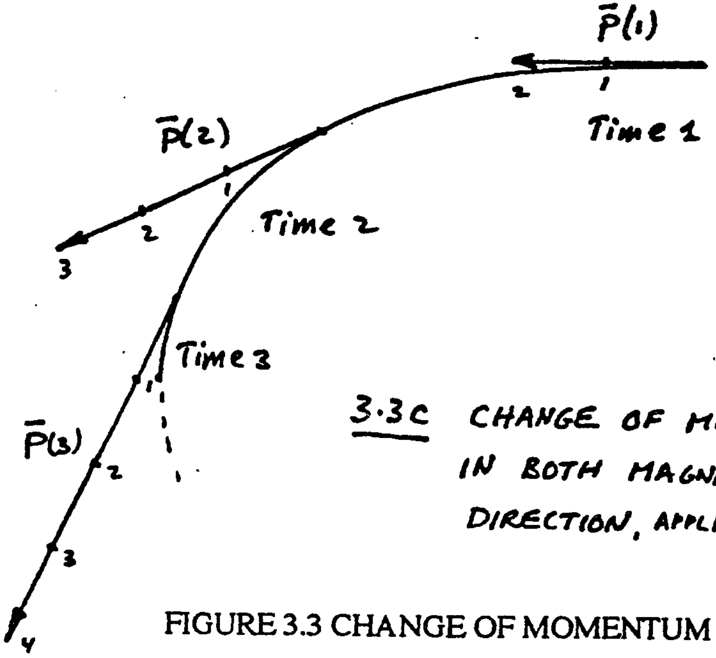
The first law is often thought of as the law of inertia as it specifies that it requires (external, motive) forces to change the state of a given body. The hidden condition in the statement of the first law is that it requires a *non-zero resultant of the impressed motive forces* to change the state and *not* necessarily that all individual forces be zero. Thus we



3.3a CHANGE OF MOMENTUM VECTOR IN MAGNITUDE ONLY BECAUSE MASS IS CONSTANT, CHANGE IS IN SPEED ONLY APPLIED FORCE IS IN THE SAME DIRECTION AS $\overline{P}$

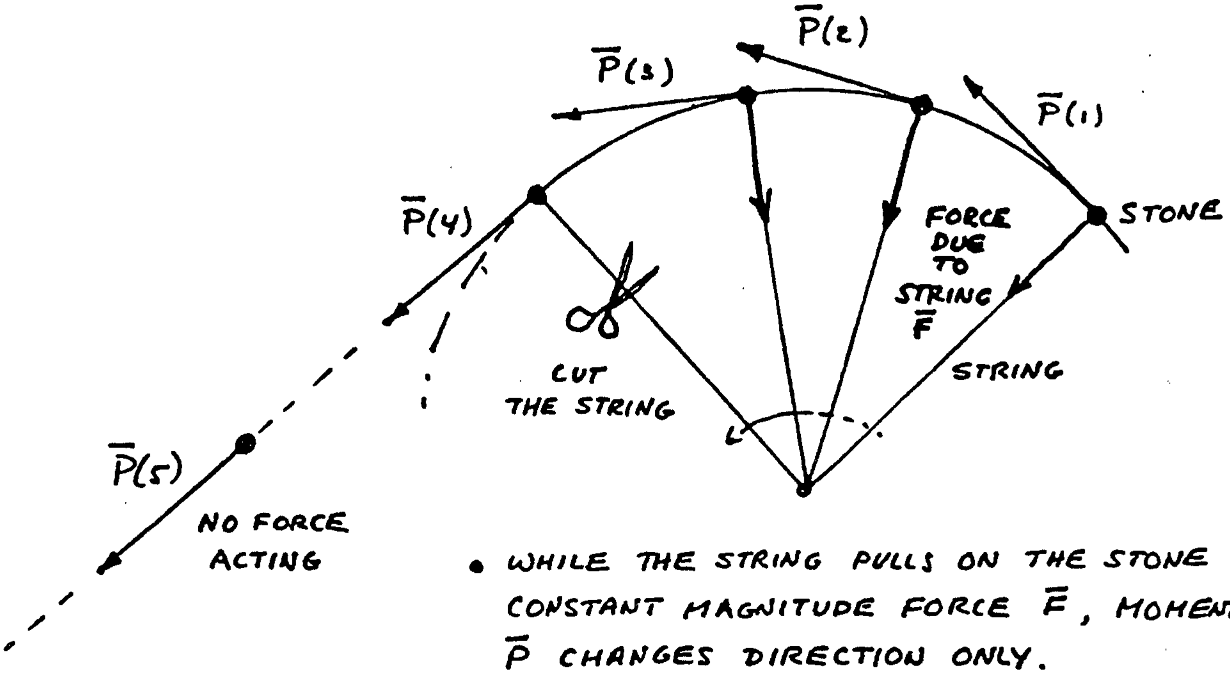


3.3b CHANGE OF MOMENTUM VECTOR $\overline{P}$ IN DIRECTION ONLY, MAGNITUDE STAYS CONSTANT. APPLIED FORCE CONSTANT IN MAGNITUDE, PERPENDIC TO $\overline{P}$



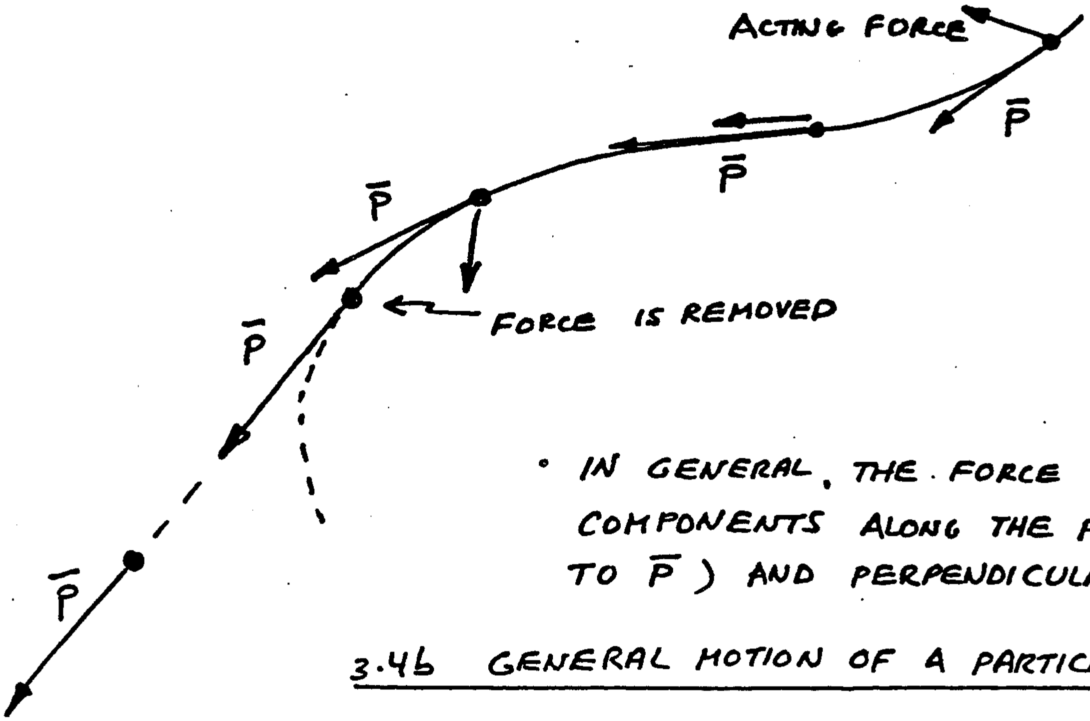
3.3c CHANGE OF MOMENTUM VECTOR $\overline{P}$ IN BOTH MAGNITUDE AND DIRECTION, APPLIED FORCE CHANGES

FIGURE 3.3 CHANGE OF MOMENTUM



- WHILE THE STRING PULLS ON THE STONE WITH CONSTANT MAGNITUDE FORCE $\overline{F}$, MOMENTUM $\overline{P}$ CHANGES DIRECTION ONLY.
- WHEN STRING IS CUT, FORCE BECOMES ZERO, MOMENTUM $\overline{P}$ REMAINS CONSTANT IN MAGNIT AND DIRECTION.

3.4a STONE ON A STRING EXAMPLE



- IN GENERAL, THE FORCE MAY HAVE COMPONENTS ALONG THE PATH (PARALLEL TO $\overline{P}$) AND PERPENDICULAR TO $\overline{P}$

3.4b GENERAL MOTION OF A PARTICLE

FIGURE 3.4 MOTION BEFORE AND AFTER A FORCE IS REMOVED need the "fourth law" of the resultant of a system of forces to decide whether the body will remain at rest or continue in its state of uniform motion.

This analysis of the first law thus introduces the concept of the *state of equilibrium* of a body. Conventionally, one speaks of *static equilibrium* if the initial state of the body is one of rest. So if all the external impressed forces form a resultant of zero, the body remains at rest - in a state of static equilibrium. Now Newton put the state of uniform motion (constant speed and direction) on equal footing with the state of rest in the First Law, so the same interpretation of static equilibrium will hold. Namely, if the body is in uniform motion and the impressed forces always act so that their resultant is exactly zero, the body will continue in the state of uniform motion. The most familiar example of this situation is that of a skydiver in free fall who reaches "terminal velocity." As the skydiver falls, eventually the forces of air drag increase until they just equal the force of gravity, yielding a resultant of zero. At this point the skydiver has reached the (constant) terminal velocity and continues to fall at a constant speed in a straight line.

Another interpretation of the first law is that the law defines two natural states for a body that is not subjected to unbalanced external forces ("For a body maintains every new state it acquires, by its inertia only"). Recall that state of a body (and we are still talking about bodies that can be idealized as particles) is defined by its velocity vector in terms of its magnitude and direction. What this means is that whatever the state of the body is at the instant that the unbalanced force resultant is removed or ceases to act, that is the state the body will persist in until another unbalanced force is introduced. This interpretation is illustrated by the familiar example (again, used by Newton) of the stone being swung in a circle. As long as there is tension in the string the stone moves in the circular path (*not* one of the natural states as defined by the first law!). At each instant of time, the stone has a particular velocity and hence momentum (Newton's quantity of motion). Because the mass is constant, the direction of the momentum vector at each instant coincides with the direction of the velocity vector. Now as soon as the string is cut (the unbalanced force is removed from acting on the stone) the body will continue in the natural state of uniform motion defined by the magnitude and direction of the velocity vector at the instant the string was cut. This is illustrated on Figure 3.4.

For the experimentally inclined, I urge you to do the experiment yourself: Release the string at different points and observe where the stone goes. The result is completely general. We do not need circular motion (as is the case for the stone motion.) After the unbalanced force is removed, every body will continue to move in a straight line defined by the direction of the velocity vector (existing at the instant the force is removed) and with a constant speed defined by the magnitude of the velocity vector. The direction will be tangent to the path at the instant the force stops (see illustration of the velocity vectors for general curving paths Figure 3.3). This illustration has clear implication for analysis of skiing situations. Whenever the turning forces on the skis are eliminated, the skier will continue in a straight line from that point on. However, for the skier the situation is more complicated and we need to consider torques as well (see chapter 4) because we are no longer dealing with the motion of a particle.The stone, for all practical purposes can be considered to be a mass particle, so the result and the illustration are quite accurate.

3.10.2 THE SECOND LAW

The second law is the key to the analysis of motion whenever unbalanced force systems act on a body. One may in fact view the first law as a special case of the second, as it follows from the second by the correct interpretation of "change of motion" whenever the resultant of the impressed motive forces is zero.

Many subsequent restatements of Newton's laws take the view that for most dynamics problems the mass of the body in question is constant. Then, since Newton's "quantity of motion" is the momentum in modern terminology and momentum is the product of mass times velocity, the second law becomes the *law of acceleration* i.e. the law is rewritten in the form that "mass times acceleration equals the resultant of the applied forces". There is, however, some benefit to be derived from thinking of the second law as the *law of momentum*, more closely aligned with the original statement: "The time rate of change of momentum equals the resultant of the applied forces." This form maintains direct contact with the first law and the concept of the natural states of a body (i.e. rest and uniform motion).

Because this law introduces the concept of "change in motion" we must keep in mind that we need a reference frame. To describe "change" we need to specify "with respect to what." The form of the second law holds true whenever we use an inertial or fixed reference frame in which to define the position and hence the velocity of the body. By the form of the law we mean that on one side of the equation we have the time rate of change of momentum and on the other we have the resultant of the external forces. When applying the second law to the analysis of skiing, the inertial reference frame is one fixed to the slope. In this reference frame, one can only measure (sense) the external motive forces. In the case of skiing, these are gravity, ski/snow interactions, pole/snow interactions and air drag. When we express the second law in a *moving* (accelerating) reference frame, however, the so-called inertial forces come into play.

For a skier, the moving reference frame is fixed to the body as are the sensors which respond to the environment. These sensors respond to the effects of acceleration (change in momentum) and these changes are what we interpret as the "inertial forces." The exact reasons why the effects of changing momentum as sensed in a moving reference frame can be interpreted as "forces" can be explained when one writes down the mathematical expressions for the second law in a moving reference frame - this is done in appendix II. The distinction between "real" forces (what Newton identified as motive forces) and "inertial" forces lies in the fact that real forces ***cause changes in motion*** and the inertial forces ***only exist as a result of changes in motion.***

So what happens in skiing is the following: We do something with our bodies, these actions change the way the snow interacts with our skis and this (real, motive) force of interaction causes the body to move in different ways (acceleration in the general sense). Or gravity acts on us as we stand on top of the hill. We remove the restraining forces holding us there and we begin to accelerate down the hill. Or we stand up from a tuck and air resistance starts to slow us down. We place the skis on edge, and the distribution of the snow actions along the edge of the ski causes us to turn. And so on. Notice that in all cases, we first do something to bring the external applied forces into play (use our control effectors) and only then something happens to our state of motion.

Since the second law states that it is the change in momentum that is equal to the applied force resultant, it follows that a more massive skier traveling at the same velocity as one less massive requires a larger force to change the velocity the same amount. This is illustrated on Figure 3.5. Suppose both skiers are traveling with the same velocity (speed and direction as shown) and wish to change their direction of travel by say 10 degrees in the same amount of time. The more massive one needs a larger force. Or, if the available force is the same, the more massive one will take longer to achieve the same direction change.

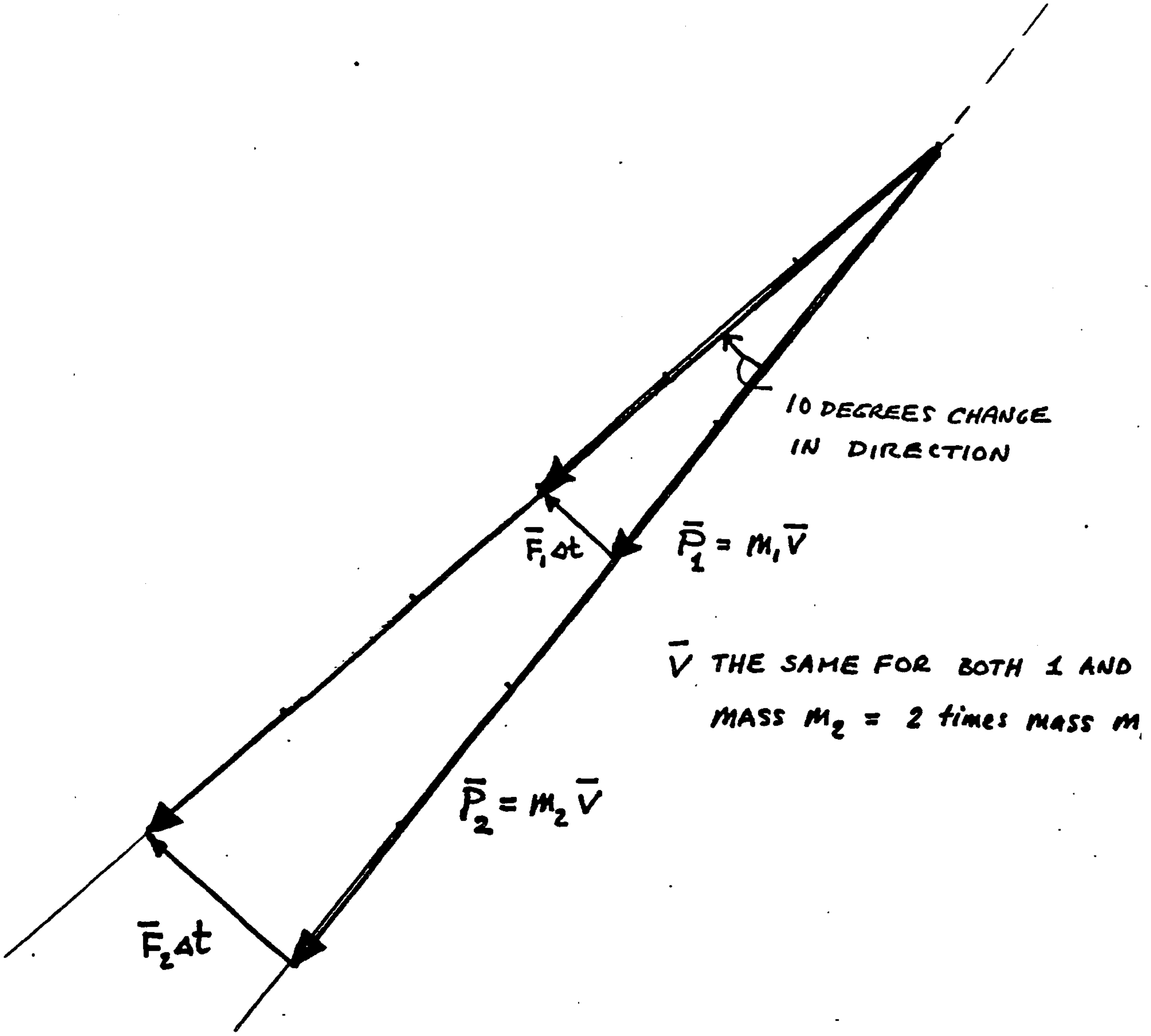


FIGURE 3.5 CHANGE IN MOMENTUM OF TWO PARTICLES OF UNEQUAL MASS

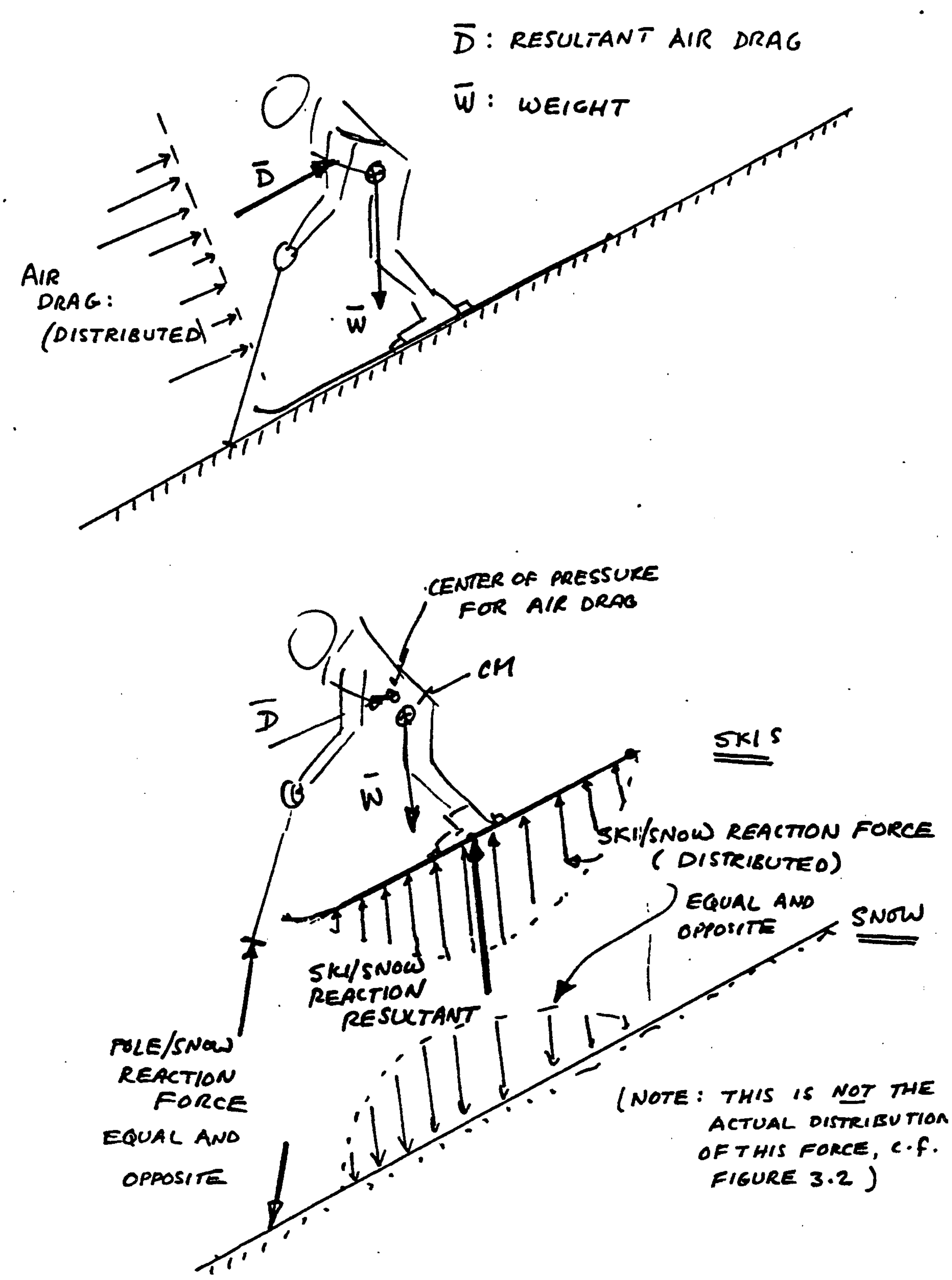


FIGURE 3.6 CONSTRUCTING A FREE BODY DIAGRAM

At this point I need to address the issue of "dynamic equilibrium." This is another jargon term often used in discussing skiing mechanics. Recall that the concept of "static equilibrium" was introduced in connection with the first law and describes the existence of a balanced set of forces. A balanced set of forces means that their resultant is exactly zero. The conclusion was that whenever static equilibrium existed, the body was in one of its natural states, either at rest or in uniform motion.

How then should we think about "dynamic equilibrium"? After all, now we have an unbalanced system of forces acting with a non zero resultant. Furthermore, no matter what this unbalanced resultant is, the second law says that the change in momentum is *exactly* equal (in both magnitude and direction) to this unbalanced resultant *at all times.* So we could say that this is "dynamic equilibrium." But what then would be the "absence of dynamic equilibrium"? In the case of static equilibrium, we know what the "absence" is: The body begins to change its natural state, either starting to move or changing its state of uniform motion. So "dynamic equilibrium" exists in all motion, no matter how awkward, or inefficient!

The way out of this dilemma is to recognize that when we speak of "dynamic equilibrium" we are really expressing our preferences for one dynamic state over another. In particular, this terminology is usually reserved for discussions of the *attitude or orientation* of a body of finite size. That is, as we move on skis, can we remain upright? As we paddle in the whitewater in a canoe, will we not tip over? The issue can only be resolved by the extension of the basic laws for particles to the motion of bodies of finite dimension (Euler's laws), which I will do in the chapter dealing with finite body dynamics (chapter 4). Suffice it to say that the concept of "dynamic equilibrium" is really superfluous for discussions of particle dynamics.

3.10.3 THE THIRD LAW

The third law allows us to deal with systems of interacting bodies. The real utility of the law is that we can replace the effects of (most) interactions among bodies by forces that they exert on one another. Newton's observation following the statement of the third law captures the essence of the concept: "If you press a stone with your finger, the finger is also pressed by the stone." For skiing, when we press our skis on the snow, snow also presses on the skis.

More significantly, the third law directs us to use the concept of a "free body diagram" when setting up a situation for dynamic analysis. Construction of a free body diagram requires the replacement of all body to body contacts with the appropriate reaction forces using the third law. The concept of the "free body diagram" is illustrated on Figure 3.6. In 3.6a I show a skier in side view descending a slope and having just planted the pole. The sketch shows the complete system of skier, skis, pole and snow, so the interactions between skis and snow and pole and snow is not shown. These interactions are internal to the system, just as the forces in the joints of the body. The air drag is a distributed force acting on the entire skier. This distributed force can be replaced by the resultant acting through the center of pressure (this concept will be defined more precisely in chapter 4). The weight similarly is really a distributed force acting over the entire body and here is shown replaced by the resultant acting through the center of mass. The illustration 3.6b shows the construction of the skier/skis/pole free body (still a collection of interconnected bodies). The effect of the snow on the pole and the skis is replaced by the respective interaction forces. The pole/snow force is effectively a point force. The ski/snow interactions are distributed as we have seen in section 3.6.4.

We can replace these with their resultant acting at a particular point on the skis. Again, what this point is will be defined in chapter 4 where other necessary concepts are introduced. Suffice it to say that this point is not arbitrary but is determined by the specific distribution of the ski/snow interactions. For completeness, I also show that the snow now experiences the pressure from the skis as well as the force of the pole. We usually don't care what happens to the snow, so this part of the free body diagrams is omitted. The concepts of free bodies and the point of action of resultant forces will play a critical role when we examine the motion of a skier taking into account the fact that a skier is not a mass particle, as required for Newton's laws, but a body of finite size.

Note that when we draw the free body diagram, we indicate (at least approximately) where the forces act and in what direction. Once we have isolated the body in which we are interested using free body diagrams, we are in a position to apply the second law. On the free body diagram we display all the external forces that exist *without contact with the body* as well as the contact forces for the bodies or surfaces we have removed. In the case of skiing, these are gravity and air resistance forces, although strictly speaking, air resistance does involve contact between the air particles and the body. As noted, we also indicate all the forces exerted by all other bodies or surfaces in contact with the one we are analyzing. In skiing, these are the ski/snow interaction forces and the pole/snow interaction forces. Some authors of mechanics texts also prefer to indicate the inertial forces on the free body diagram as well, generally using some convention such as a dotted vector representing the mass times acceleration term. However, this practice may lead to confusion so in my opinion, it's best to represent only the external motive forces.

Another consequence of the second and third laws conjointly is the following: If two bodies interact, and one is much more massive than the other, then the change in motion of the less massive body is greater than the corresponding change in motion of the more massive one. An extreme example of this is the case of a stone falling freely towards the earth. The interaction force between the earth and the stone due to gravity (both the stone and the earth have a gravitational force associated with them) is the only force acting if we neglect air drag. According to the third law, the force acting on the stone is equal and opposite to the force acting on the earth. Because the earth is so much more massive than the stone, all we see is the motion of the stone. But the earth moves infinitesimally toward the stone as well! A practical application of this result in human motion is our ability to move one body part relative to another that remains more or less immobile. For example, if the part we move (e.g. the arm) is less massive than the part against which the motive muscles work (e.g. the rest of the body for moving the arm) we will see the arm move but not the rest of the body.

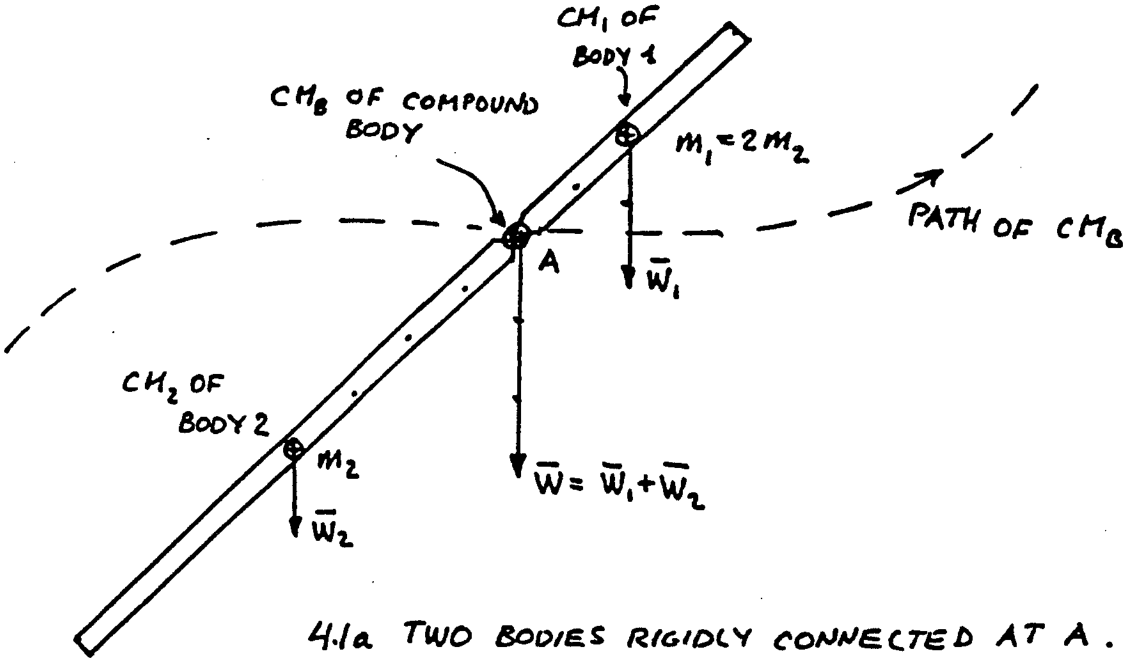
4. EXTENSIONS TO THE DYNAMICS OF FINITE BODIES

So far, the discussion has been primarily focused on the motion of particles (bodies whose physical dimensions can be neglected). For most problems of analyzing human motion dynamics we cannot neglect the dimensions of the body. Fortunately, the basic Newtonian laws for particles can be extended to the more general situation, and in fact, *the second law remains as a valid means to analyze the motion of the center of mass of the body,* where now the momentum is defined as the product of the entire mass of the body and the relevant velocity is the velocity of the center of mass. Questions continue to arise about the difference (if any) between the center of mass (CM) of a finite body and the center of gravity (CG). For those who are concerned about the fine points, I include in appendix II an explanation of the difference and why it is not significant for the motions we are discussing. We need the concept of the center of mass because we seek to replace the distributed action of gravity acting on all particles of our body with a single resultant force (our weight) and for this we need to define the point of application of this resultant force such that the effect on the motion of the body is equivalent to the effect of the distributed force. The situation is similar for any distributed force e.g. air drag or ski/snow interaction forces. For these we also need to define the point of action of the resultant.

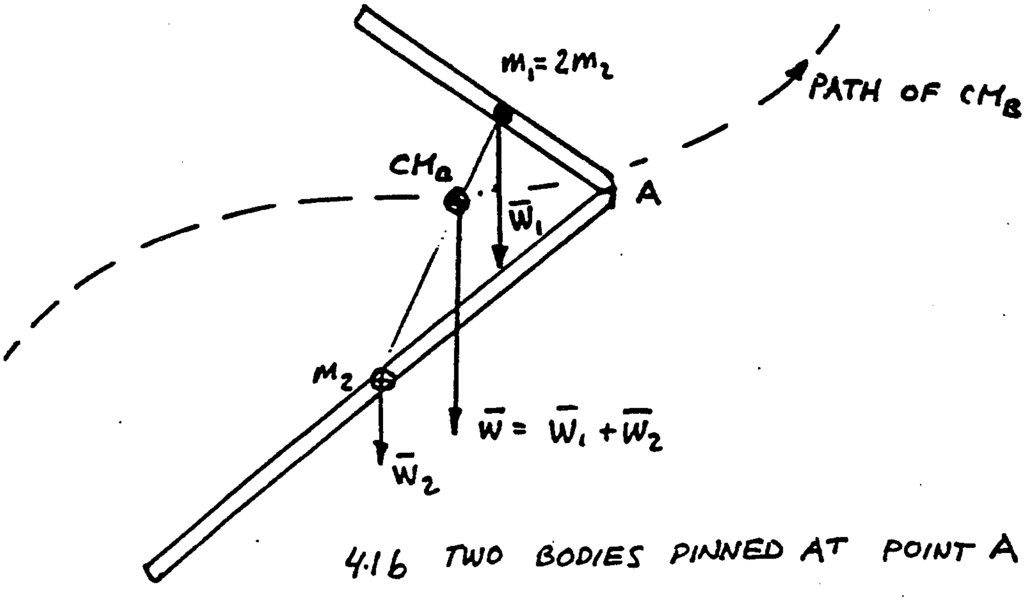
Another issue to consider is that humans are not rigid bodies, but rather a collection of connected flexible bodies. It can be shown (see Feynman [1] or Sommerfeld [9]) that even for this situation, the second law still governs the motion of the CM. That is, we can consider the CM as a particle with all of the body mass, then apply all the external forces to this particle to study its path in space. For systems of interconnected bodies which may rearrange their configuration, the overall CM will not be any specific fixed point of the bodies. It will move around and in fact will often lie outside the bodies. The example for human motion is easy to visualize: When a diver executes a layout dive, the CM is roughly inside the body near the navel, when the diver moves into a pike position, the CM moves outside the body into the area within the V formed by the pike position. Even though the CM moves around, the second law still determines the path of the CM through space! To determine the path of the CM of a compound body through space, we do not need to consider the point of action for the resultants of the distributed forces, only their magnitudes and directions. These ideas are illustrated on Figure 4.1. On 4.1.1 I show two bodies rigidly connected at the point A and the CM of the compound body made up of the upper and lower parts is located at the joint. (This is so since one body is twice as massive as the other and the less massive is twice as long as the more massive one. If this were not so, the CM of the compound body would be located at a different point, but still within the body.) On 4.1.2 I show the same two bodies but now they are pinned at the point A so that they are free to rotate with respect to each other. At the instant shown, when they are in the pike position, the CM is outside the body.

As I have indicated, the problem of directing the motion of the CM of a rigid body or a connected set of bodies through space is one of *guidance.* That is, we manage the available external forces in such a way as to get the CM to follow the path we desire at the speed we choose. If we don't care about the orientation of the body (do we remain upright or not in the case of skiing), then Newton's law applied for the CM is all that we need for most discussions.

When we consider the possible general motion of a skier, we need to be very careful in how the various forces are treated. For particles, the issue of where a given force acts does not arise, since the particle by definition has no physical dimensions. When we consider bodies of finite size, the point of application of external forces is important. To



4.1a TWO BODIES RIGIDLY CONNECTED AT A.



4.1b TWO BODIES PINNED AT POINT A

FIGURE 4.1 CENTER OF MASS OF A COMPOUND BODY determine the motion of the CM, we translate all forces from their actual point of application to the CM. For this to be valid, we also need to introduce a moment due to the force about the CM. I will clarify these issues next as part of discussion of general rotational motion of bodies.

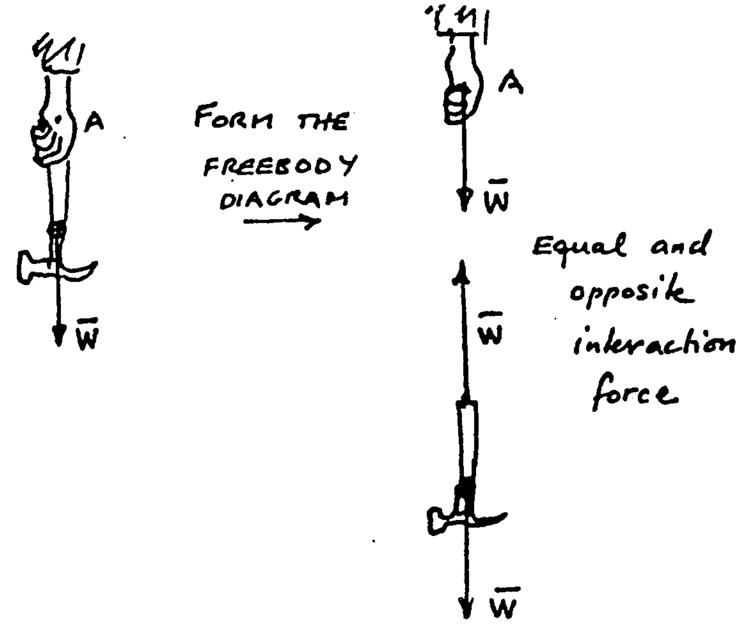
For the discussions of rotational motion in a general sense I need the concepts of a couple, a torque and the effective moment of a force about a point. In engineering usage, these terms are carefully distinguished; in physics, torque and moment of a force are used interchangeably. "Torque" is derived from *torquere* Latin for "to twist."

The origin of the term "moment" is obscure, but in engineering and mathematics it means "weighted by the distance from an axis." So applying this concept to mechanics, I have the magnitude of the moment of a force about a point defined as the magnitude of the force times the perpendicular distance from the line of action of the force to the point. The magnitude of the resultant quantity is the torque. The key idea here, and what separates a moment from a couple (defined next) is that a moment depends on a point of reference as well as the magnitude of the force creating it.

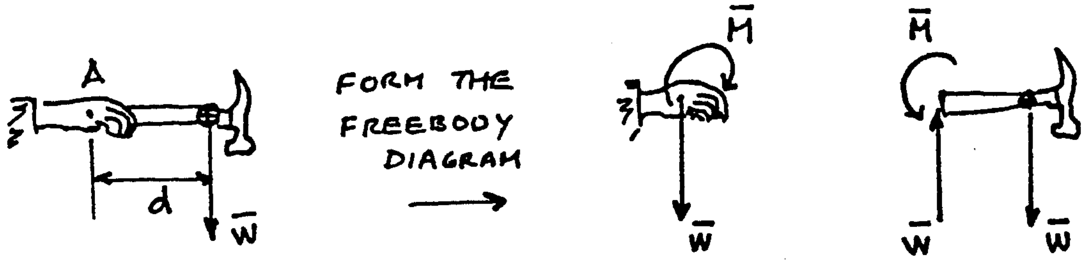
I illustrate this concept on Figure 4.2. If you experiment with the hammer or any other object in the manner shown, you will have a clear understanding of what a moment due to a force is and the significance of the line of action of the force in relationship to the point of reference. In 4.2a I show the hammer hanging straight down. In this case the line of action of the weight passes through your wrist and you feel no torque there. In 4.2.b the weight of the hammer acts a distance d from the wrist and you feel both the weight and a moment in the wrist.

A couple on the other hand always involves the action of two force vectors (of equal magnitude but opposite direction) in such a way that the torque of a couple is the same for all points. Because moments and couples are the result of vector action, they also are vector quantities with a sense of direction associated with them. The sense of a moment or couple is defined mathematically in appendix II; for the purposes here we can think of the sense as defined by whether the body will rotate clockwise or counterclockwise under the action of the moment or couple. This is indicated by a curved vector and the direction is indicated by an arrowhead. Thus, on the freebody of the hand we show a clockwise moment arrow and the force due to the weight. (Of course, we do not have a complete freebody drawn of the hand since I assume that the hand is still attached to the body which I have not shown!)

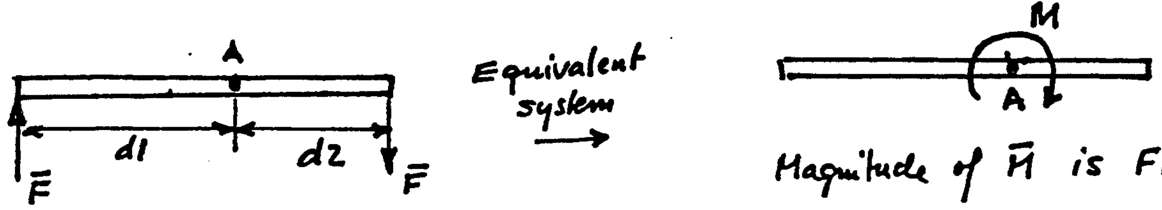
To account for the effects of a distributed force on a body, such as the ski/snow interaction force, we need an intermediate step before determining the equivalent force and moment about the CM. I need to explain how you find the point where the resultant of a distributed force should act (This issue was introduced in section 3.10.3 in connection with the third law and drawing free body diagrams). Let's first consider that instead of a true distributed force, which is defined as one that acts on every point of a finite body, we have a limited number of single forces acting at different points on the body. This situation is illustrated on 4.2.d for four forces. The point of action of the equivalent force is determined by requiring that the moment about any selected point (in the illustration, the point P at the left end of the bar) due to the resultant be equal to the sum of the moments of each individual force acting. The choice of the reference point is arbitrary - you will get the same result if you select the right end, for example. The magnitude of the resultant is the usual sum of the magnitudes of the individual forces. The same basic method is used in the case of a true distributed force except then one



4.1.a Line of action of a force acting through the point A

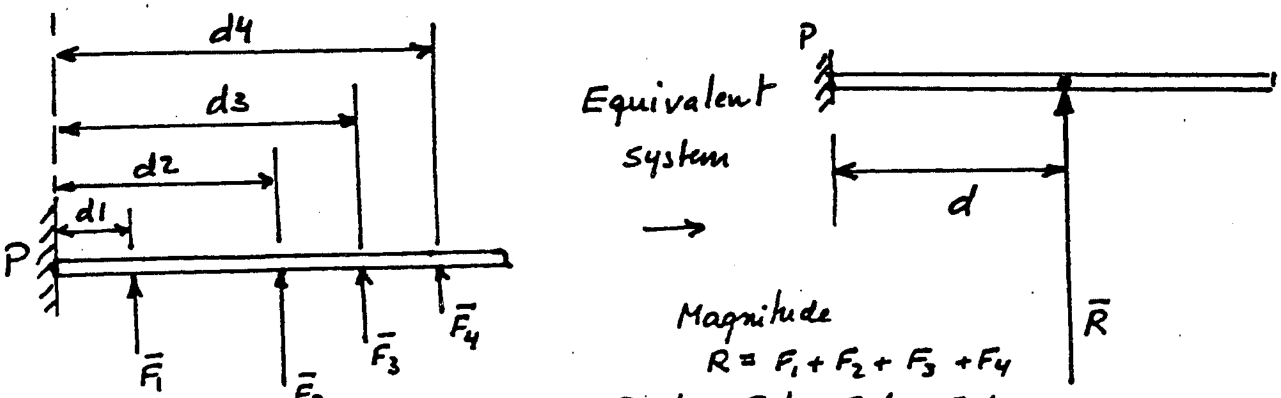


4.1.b Force acting a distance d from point A Magnitude (torque) of M̄ is W.d, sense as shown.



Magnitude of M̄ is Fd1+

4.1.c A couple acting on a body



Magnitude

$R = F_1 + F_2 + F_3 + F_4$

$R \cdot d = F_1 d1 + F_2 d_2 + F_3 d3 + F_4 d4$

FIGURE 4.2 FORCE AND MOMENT SYSTEM EQUIVALENTS must use the methods of integral calculus rather than the simple addition we use in the case of finite number of forces.

Why is all this important? Skis and skiers turn because they manage the ski/snow interaction forces so as to create a moment or torque about some axis. They can also exert couples (or "pure twisting") via suitable body movements. Sometimes these will cause the skier to turn, other times not. This is so because by definition a couple always involves two equal and opposite forces and thus by itself will contribute a net zero force to change the path of the CM. The activity of applying a couple must bring into play some other forces with a non zero resultant for the trajectory of the CM to change. A related concept is that of a "pure torque" such as we apply when we are wring ing out a wet towel. A pure torque also imparts no resultant force on a body. As we have seen, in contrast to the couple and the pure torque, a force acting some distance from a point can exert a torque and have a non zero resultant acting on the CM, thus changing the path of the CM. For example, when we plant the pole, the pole-snow interaction force acts a distance from the CM so this force exerts a moment about the CM. Thus the effects of a pole plant can involve a force that contributes to the path the skier takes, a turning moment or a moment that can aid in balancing.

In Figure 4.3 I illustrate these ideas for a representative skiing situation, where for simplicity I neglect the effect of air drag. First, I have to identify the point where the resultant of the distributed ski/snow interaction force acts. I choose to resolve this force into the normal (perpendicular to the skis) component and the component parallel to the ski bottom (friction force). Then, I identify the distance from the line of action of each of these force components to the CM. The magnitude of the equivalent moment is the product of this distance times the magnitude of the corresponding force component. The sense of the moment due to each component is again represented by the arrow head on the arc. For the illustration of Figure 4.3, we see that the moment due to the normal force is clockwise and that due to the friction is counterclockwise. So if the skier wants to avoid falling forward, thenormal reaction force must result in a clockwise moment, that is, the skier must “sit back” slightly. Of course, if the friction force suddenly decreases and the body cannot adjust to this, the skier falls backward.

Thus, the new feature that is brought about by considering the finite dimensions of a body in motion is the determination of the *attitude or orientation of the body* with respect to some reference. This is clearly of interest to us as skiers, as we do wish to remain upright with respect to the surface of the snow as we ski. The laws governing the attitude of a rigid body can be derived from the fundamental three laws of Newton by considering any body to be composed of an infinite number of small particles, each of mass m_i and possessing a velocity $\vec{v}_i$ (the arrow over the v indicates that v is a vector). Then the second law is applied to each particle. Finally, one sums over all the particles of the body (for continuous bodies the summation becomes the integration operation of calculus). Applying the third law (the equal and opposite nature of the interaction forces among all particles) leads one to the following conclusion: The complete specification of where the body is in space and how it is oriented with respect to that space requires the second law for the *motion of the CM* and a similar law for the *motion about the CM* (known as Euler's law). The mathematical similarity of these laws is displayed in appendix II where I present the explicit mathematical forms. The specification of the orientation of a body in space and the change of orientation is illustrated on Figure 4.4.

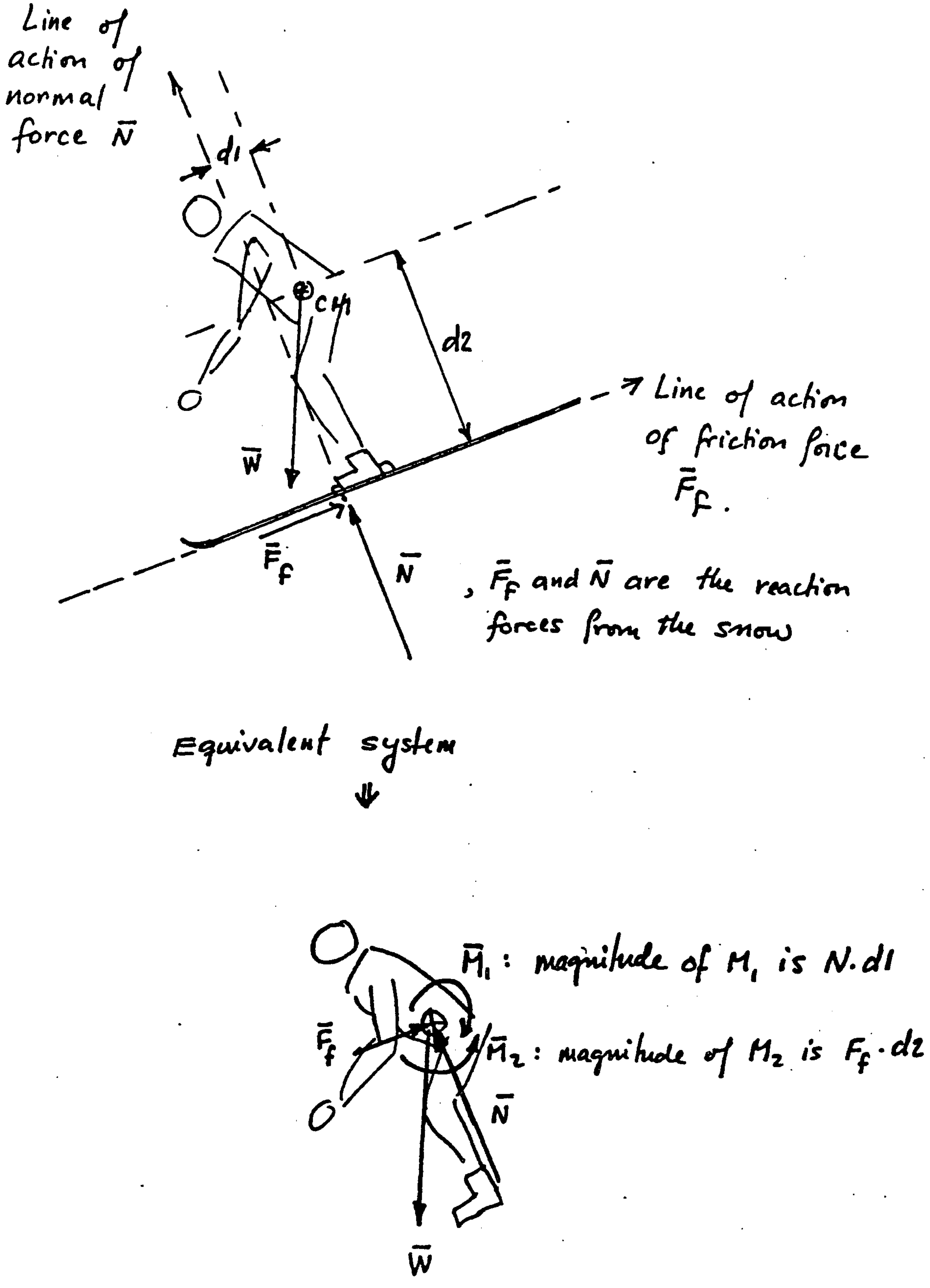
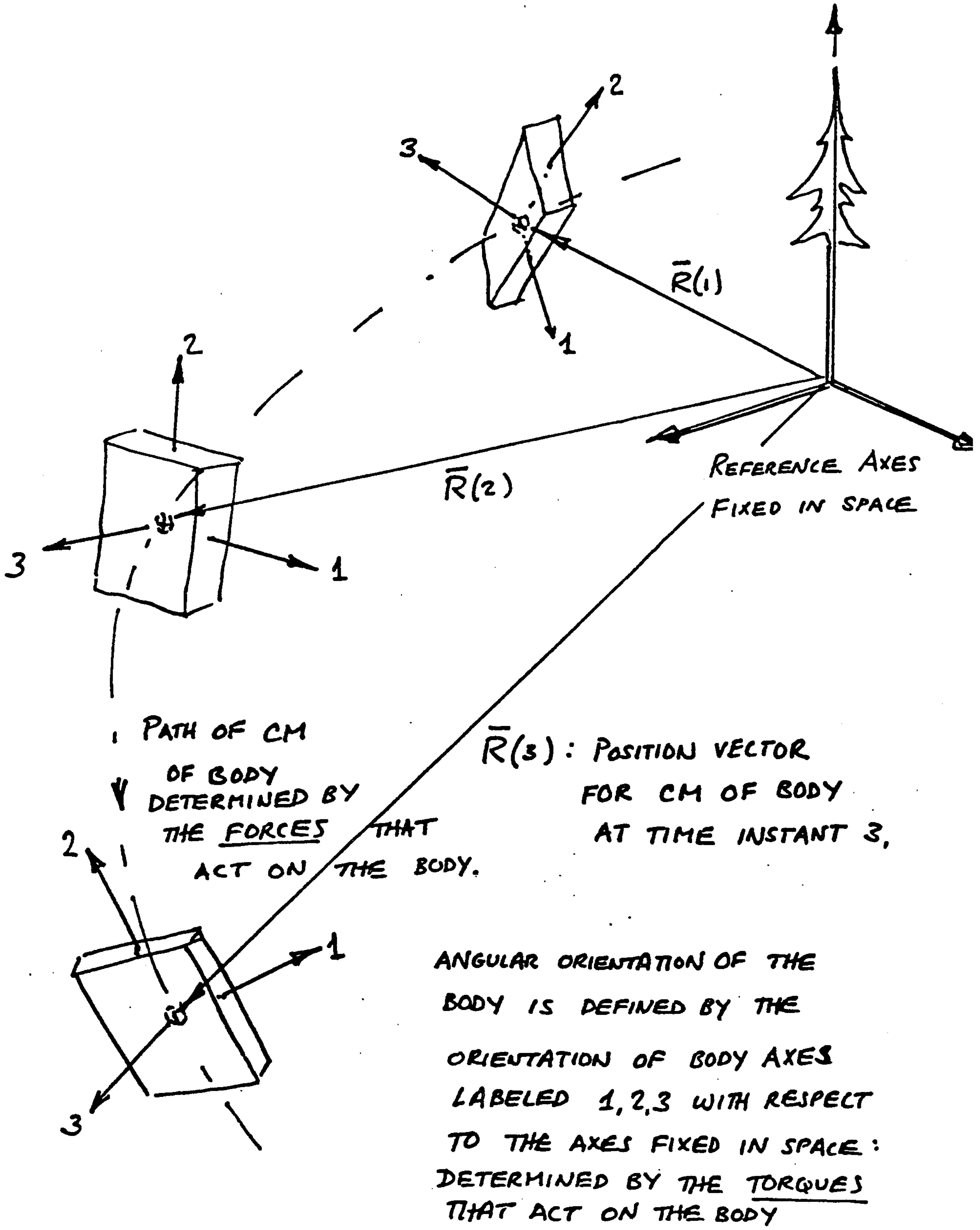


FIGURE 4.3 EQUIVALENT FORCE-MOMENT SYSTEMS



REFERENCE AXES FIXED IN SPACE

PATH OF CM OF BODY DETERMINED BY THE FORCES THAT ACT ON THE BODY.

$\bar{R}(3)$: POSITION VECTOR FOR CM OF BODY AT TIME INSTANT 3,

ANGULAR ORIENTATION OF THE BODY IS DEFINED BY THE ORIENTATION OF BODY AXES LABELED 1,2,3 WITH RESPECT TO THE AXES FIXED IN SPACE: DETERMINED BY THE TORQUES THAT ACT ON THE BODY

FIGURE 4.4 GENERAL MOTION OF A RIGID BODY

Euler's law for the attitude motion of a rigid body can be paraphrased in a manner similar to Newton's second law:

The change in angular motion about the CM is proportional to the resultant of the motive moments impressed and is in the direction of that resultant impressed moment.

Another version, symmetrical to Newton's Second Law, when that law is expressed as:

The time rate of change of momentum is equal to the resultant force.

is the following:

The time rate of change of angular momentum is equal to the resultant torque.
This is loosely paraphrased in a manner analogous to what was done for Newton's Second Law:

If an unbalanced torque acts on body, its angular motion will change.

As was the case with Newton's Second Law, I need to explain the content of Euler's law. As will be seen, all the quantities are vectors, just as for particle motion. First, *angular motion* refers to the angular momentum of the body. It is analogous to the concept of linear momentum we encountered in the study of particle motion. Angular momentum of the body is defined by the angular velocity and the mass distribution of the body conjointly. This again parallels the particle dynamics situation where momentum is defined by the product of velocity and mass. The angular velocity is the rate at which the body changes its orientation with respect to a fixed set of reference axes. Angular velocity describes in general what one may think of as spin or rotation. The term applies to very general rotational motion, from simple spin about one axis, as is the case of a figure skater's spin, to a general tumbling motion that we see when a large rock bounces and tumbles down a slope.

In the case of particle motion and Newton's laws, the property of the body that determines how hard it is to change the state of motion is the body inertia. The mass is a measure of the inertia. For rotational motion, there is an analogous property - the moment of inertia - that determines how difficult it is to change the rotational state of the body. The larger body moment of inertia, the harder it is to start it rotating or stop it from rotation. The moment of inertia is defined for each body with respect to specified axes and is determined by how much mass the body has and how that mass is distributed relative to the axis in question. Hence the term "moment of inertia" (see discussion above regarding the moment of a force).

The resultant of the impressed moments (total torque) is the vector resultant of the moments of each impressed force, defined as the force times the perpendicular distance from the line of action of the force to the CM of the body, plus any couples. For particle motion, a force is what is required to change linear motion, the thing that makes something rotate is a torque. If there is no resultant torque on the body, its rotation will not change.

The significant observation from all this is that if the resultant moment or torque about the CM is zero and no rotation already exists, the angular orientation of the body with respect to the reference frame will not change. This follows from Euler's law, since the resultant torque is zero, angular motion does not change. Since the resultant moment or torque is a sum of the moments of force, plus any couples and "pure torques", for the resultant to be zero we need the couples and pure torques to be identically zero. For the moment of a force to be zero, either the force itself must be zero *or it's line of action must be through the reference point, in our case through the body CM.* This last requirement is the key issue for skiers and the mechanical analysis of the problems of balance. As long as the resultant force due to all the forces passes through the CM, there will be no moment acting on the body as a whole and no tendency to tip or fall.

The term *balance* implies controlling the desired orientation of a finite body with respect to a fixed reference frame in face of varying and uncertain disturbances. A "disturbance" in the context of dynamics means a force or a torque that we did not intentionally create. So the term *balance* really should be used in the active sense: We perform *balancing movements* which are intended to manage all the forces acting on us in such a manner as to keep their resultant moments about the CM equal to zero. Euler's law then assures us that no change in orientation will take place i.e. we will not fall.

Now, the situation is really a bit more complicated than that. Because if there were no resultant torques about the CM at all, we would ski in very strange ways indeed. Euler's law is a vector law just as is Newton's law. For particle motion, to define the location of a point in space, we need to specify three reference axes and there is a scalar equation that describes what happens in each axis. Similarly, to describe angular orientation, we need to specify three reference directions (axes). Again, we can use axes fixed to the slope or fixed to our bodies. Let me define axes fixed to the body as 1) front to back, 2) head to toe (longitudinal) and 3) side to side (lateral). (I will give a more precise definition in the section on biomechanics, chapter 7). Then, at each instant as we ski down the hill, we try to minimize rotation about the lateral axis and the front to back axis. This is what we mean when we say that good skiing requires good fore-aft balance and good lateral balance. In other words, we try to keep a centered stance on the skis. Rotation about the longitudinal axis is allowed to vary as we make turns down the mountain. Note that I say "minimize", since some rotation about the other axes is desirable to control body lean and/or angulation.

I can now return to the issue of "dynamic equilibrium". By dynamic equilibrium, I mean that the body will remain essentially upright as the skier travels down the slope. To do so, the skier needs to manage the reaction forces on the skis and his or her body orientation in such a manner as to keep the moments due to these forces about the lateral and front to back axes equal (or close) to zero. Since the reaction forces are changing rapidly and continuously as we ski, maintaining an upright body orientation is a nontrivial task. However, we do not need to work with the details of the equations governing the motion about the CM to understand what is going on. We only need to know that the goal of whatever we do is to keep the appropriate resultant moments zero. The line of action of gravity is always through the CM as are the lines of action of all the inertial forces, so this means we only need to worry about how the ski/snow and pole/snow reaction forces work and, at high speeds, how air drag works. In general, we are concerned with lateral balance (side to side tipping) and fore-aft balance. For lateral balance, the resultant moment about the front to back axis must be zero. So if we view the skier from the front (the way most technical analyses of skiers portray the motion in a turn) then the line of action of the resultant ski/snow reaction force must be through the CM. Similarly for fore-aft balance, the resultant moment about the transverse (side to side axis) must be zero. This is usually ensured by maintaining a centered stance over the skis and "avoiding the back seat" in instructor jargon.

I can contrast this with the situation for the motion *of* the CM. There, the primary objective is to *change* the path down the mountain as well as vary the speed. To do this, the skier needs to introduce unbalanced forces. Remember that the natural state for the body is to be at rest (not very interesting for the skier) or in a state of uniform motion (a bit dangerous for the skier as all straight lines on the mountain eventually intersect an immovable object!).

It is of interest to note that different sports may require focus on either Newton's law for the CM or Euler's law for motion about the CM or both. For example, divers are primarily concerned with Euler's law as the trajectory of their CM is largely determined by the forces between the diving board and the feet at the instant of takeoff. The trajectory of the diver's CM is a parabola and little can be done to alter it. On the other hand, as the divers execute different dives, they are playing with Euler's law of angular momentum in intricate ways. For skiing, we normally prefer to keep the body upright, so the focus is to manage the ski/snow forces in such a way that the trajectory of the CM does what we want. Also, these forces ought to contribute zero moments about the CM in the lateral and front to back axes, so as to keep the angular momentum about these axes close to zero at all times. In contrast, free style skiers in the bumps who throw in some aerials must deal with both laws appropriately.

5. CONCEPTS OF WORK AND ENERGY AND APPLICATION TO SKIING

An alternative approach to analysis of skiing is based on the derived concepts of work and energy that follow from Newton's laws of motion. By operating mathematically on the second law of motion (see appendix II) I can deduce that:

"The change in kinetic energy of a moving body is equal to the work done by the external forces acting on the body".

To help you understand this relationship, I need to re-state the definitions of energy and work in the technical sense that I need them. First, let's look at "work." Work is defined as the component of force acting along the path on which the body moves times the path length (the distance along the path). Because the force(s) may act in any general relationship to the path, we need to only consider that component that acts along the path (Figure 5.1). As a consequence, a force that always acts strictly perpendicular to the path (at right angles to the path) will do no work. This idea was introduced in section 2.3 - here I expand on it.

The energy of a body is a measure of the capacity of the body to do work. A body does work on the environment through the mechanism of the interaction forces with the environment. Conversely then, the environment can do work on the body through the same mechanisms. Specifically, in the case of skiing, the snow/ski interaction forces, the pole/snow forces and the air drag forces have the capacity to do work on the body and thus change the energy of the body.

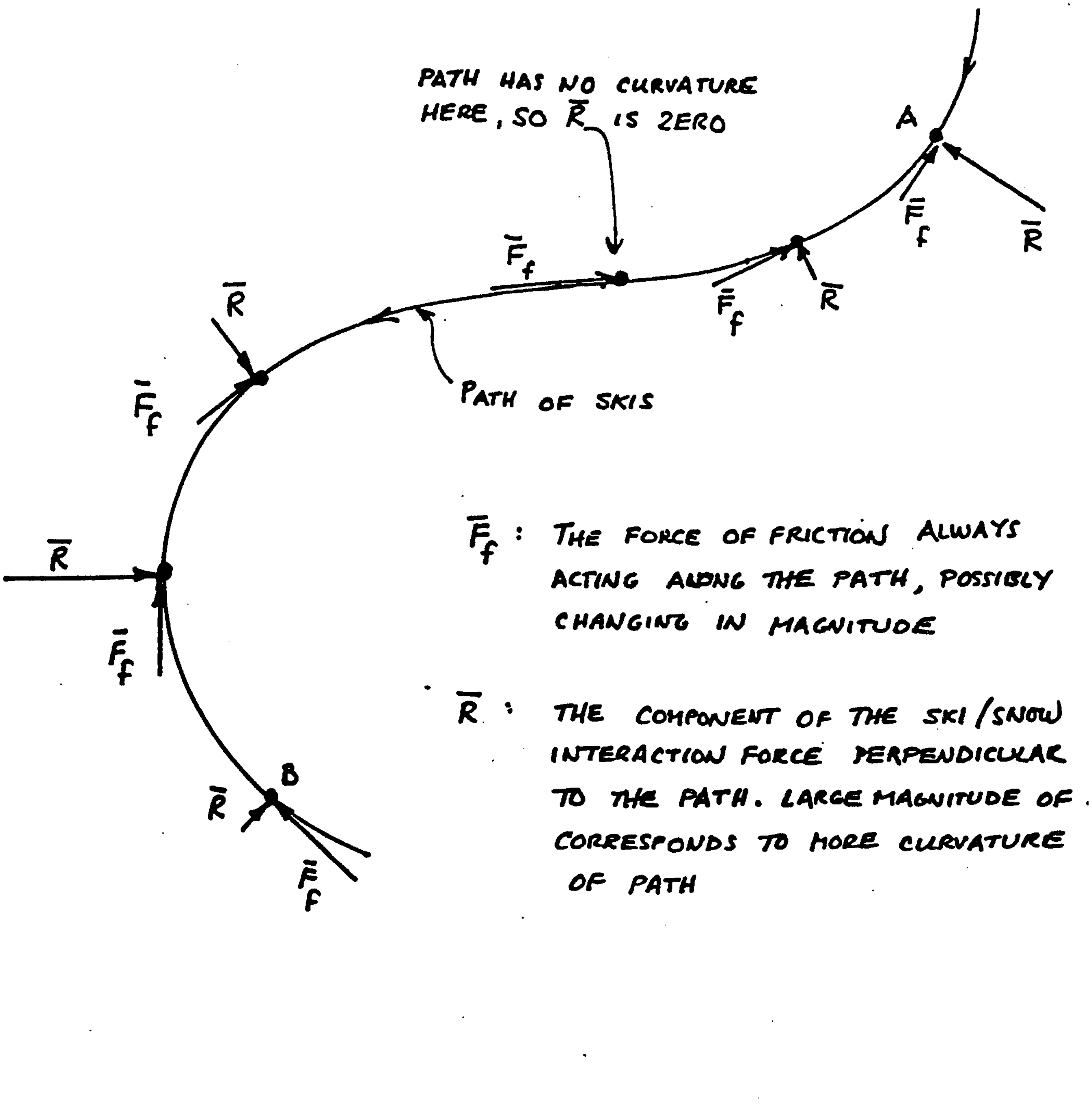
For skiing applications, we are interested in three forms of energy: The kinetic energy (energy of motion), potential energy (energy due to our position in the gravitational field of the earth, energy in a ski due to it's deflected shape), and muscular (internal) energy. In addition to these forms, we are also interested in energy loss or dissipation mechanisms. These mechanisms remove energy from a body that cannot be recovered, for example, energy loss through friction effects between the skis and snow, air drag, or the more complicated mechanics of shearing of the snow surface by a skidding ski.

The major source of potential energy is the gravitational field and indeed, in skiing, this is always the basis from which we start. Standing at the top of the mountain, courtesy of the lifts and the management, we have maximum potential energy available from gravity. In addition, there is a relatively small amount of energy we can derive from our muscles. The energy that we gained by being lifted to the top of the mountain, plus whatever losses due to friction exist in the lift., is exactly equal to the energy spent by the lift (which may be electrical or petrochemical). Potential energy is just that - it is the source of energy for motion.

Kinetic energy is the energy of motion and is a measure of speed and rotation rate. For a body of finite dimensions, the total kinetic energy is composed of a part due to the motion *of* the CM plus that due to the motion *about* the CM. For analysis of the skier's motion down the slope, we are concerned only with the part due to the motion of the CM. This is given simply by one half the product of the mass times the speed of the CM squared:

1/2 (mass)x(speed)x(speed) = kinetic energy of the CM

By working with Newton's laws, one can show that there are specific relationships between kinetic energy, potential energy and the action of dissipative forces. For the case



$\bar{F}_f$: THE FORCE OF FRICTION ALWAYS ACTING ALONG THE PATH, POSSIBLY CHANGING IN MAGNITUDE

$\bar{R}$: THE COMPONENT OF THE SKI/SNOW INTERACTION FORCE PERPENDICULAR TO THE PATH. LARGE MAGNITUDE OF CORRESPONDS TO MORE CURVATURE OF PATH

FIGURE 5.1 WORK DONE BY FORCES

where there are no dissipative forces acting, the total energy of the body (defined as the sum of kinetic and potential energy) is conserved. So for motion where only gravity acts, potential energy is exchanged for kinetic energy and vice versa. The potential energy due to position in the gravitational field is defined explicitly in appendix II.

A simple example that approximately exhibits this behavior is the simple pendulum (a mass hanging on a string). If I hold the mass above the rest position, the mass has a given amount of potential energy. When I let it drop, the potential energy decreases and the mass gains speed (kinetic energy). At the bottom of the swing, the mass has it's maximum speed and minimum potential energy. Then, as the mass starts up again, it loses speed, gains potential energy until it is at rest at the extreme of the swing. Then the cycle starts again. Of course all real systems have dissipative forces acting and a real pendulum will eventually settle down in the minimum potential energy configuration i.e. hanging straight down. As the amplitude of the oscillations progressively decreases, there is less potential energy available for each swing and thus the speed of the mass at the bottom of the swing will be less and less, until motion stops completely.

The situation is similar for skiing. As you start down the mountain, you gain speed, thus kinetic energy, and lose potential energy. You also lose energy to the surrounding air and to the snow surface. If there were no losses to the environment, all the potential energy would be converted into speed. Thus to maximize speed down the mountain you need to minimize the losses. This is true whether you travel in a straight line (speed skiing) or in some curved path (e.g. slalom course). The result applies to the entire run or on a turn by turn basis. The total lost energy is the sum of all the little losses at each stage of the run.

Let's return to the basic work-energy relationship: The change in kinetic energy (which is equivalent to the change speed as the mass is constant) is equal to the work done by the acting forces. This is not an obvious result and you must take it as a matter of faith. It is proved in appendix II using the methods of mathematics.

It is intuitively obvious, however, that a retarding force will decrease speed and a propulsive force will increase speed. The propulsive forces for skiing are gravity and the muscles (skating or poling) and the retarding forces are air drag and snow/ski reactions. You use the muscular forces to increase speed in slow sections by skating or poling; these rapidly become ineffective as the speed goes up. So the application of the work-energy relationship will primarily deal with what you do to manage air drag and the ski/snow interaction forces. Air drag is relatively simple: To speed up, you need to present as small a frontal area to the air stream concurrently with assuming the most streamlined shape that you can via clothing and body configuration (tuck stance, leg separation, arm and hand position, attitude of the tuck etc.). To slow down via air drag, you stand up and increase the frontal area as much as possible. These are the only uses that you have for air drag. By contrast, the ski/snow interaction forces have a multitude of roles to play: They provide the turning forces and balancing forces, as well as speed control.

6. COMMON MISCONCEPTIONS ABOUT MECHANICS

Because there are so many misconceptions about mechanics that enter technical discussions, I thought it beneficial to address the most common ones encountered over the years. A major reason for misconception is not clearly understanding the concept of ***cause and effect.*** When discussing the mechanics of human motion, this concept is particularly important. You want to control and guide your motion, so you need to understand that you are continuously interacting with the forces that exist between you and the environment. What you have under direct control are the actions you can take with your body *not* the reaction forces between the equipment and the snow. So skiing is really the act of manipulating the way the ski/snow and pole/snow reaction forces act on your skis and poles. Of course, ski/snow interactions are a two way street. In addition to providing the means to achieve motion that you desire, these interactions are the major source of disturbances that you must counteract.

Another problem area is in developing a clear understanding of what centrifugal force is, as well as understanding the concept of a centripetal force. In fact, many difficulties in thinking about skiing mechanics can be traced to confusion about the true nature of forces and the need to separate external, motive forces from inertial forces. The key is that external motive forces *cause* changes in motion, inertial forces are the result. The concept of centripetal force is discussed in detail in section 3.6.1. As noted there, the principal difficulty with the notion of centripetal force is that one may bring this concept into the discussion *in addition to* the ski/snow interaction forces as if centripetal force were something different from the radial (inward acting) component of the ski/snow interaction force. Centrifugal force is discussed in section 3.10.2, with the definition developed in appendix II. To summarize the discussion, we need to understand that we sense what is going on with respect to our bodies, which are in motion. In this moving (accelerating) reference frame, centrifugal force is real. We sense it as if it is a force trying to move us toward the outside of the turn. It is *not* momentum, nor is it inertia, as is sometimes thought. Inertia is a property of the body, defined in section 3.5. Likewise centrifugal force is *not* momentum. It is one component of the *change* in momentum, as dictated by the second law of motion.

Occasionally, force gets confused with (linear) momentum. Linear momentum is the product of your mass times the velocity. Force is required to change momentum. One does not use momentum to create force. This is once again the issue of cause and effect. The second law clearly states that the *time rate of change of momentum* is equal to the resultant of the forces acting on the body. Because of this relationship, we see that if a body has large momentum (by virtue of having a large mass or velocity or both) then significant changes in that momentum are going to require large forces (see for example the illustration on Figure 3.5). If we consider the example of running into a stationary object, we can see how this works. Some motive force was required to get you moving at a high rate of speed to impart large momentum. Now, when you run into the object, to stop you (remove all momentum) the object must be capable of generating a large force. Your momentum did not create the force. Similarly, for rotational motion we must distinguish between angular momentum and torque. Torque is required to change angular momentum.

The role and nature of friction in skiing is also a source of confusion. For example, is friction required for ski turns? A detailed discussion of friction and how it enters ski/snow interaction forces is given in section 3.6.2. Here I only emphasize that friction is *not* the primary determinant of whether you turn or not. Rather, the way and extent of the ski penetration of the snow surface and the structural properties of the snow will determine what the effects on the motion will be.

One of the most persistent notions in ski technical discussions is the concept of "weighting" or "un-weighting " and how one is to accomplish these results. This notion, and the attendant concept of "weight transfer", have been integral parts of ski technique explanations since the beginning, and continue to torment exam candidates at all levels. In connection with these concepts, one is also forced to figure out how flexing and extending influence weighting, un-weighting and weight transfer. It is worthwhile to spend some time on this issue here as well.

In the first technical manual of American ski instruction, titled The Official American Ski Technique (the "white book"), published in the 60's, one finds up-unweighting and weight transfer as two of the "seven basic principles" of the American ski technique. The definition of *up-unweighting* was given as: "The reduction or elimination of the skier's weight on the snow by a quick upward extension of the body. The up-motion is immediately followed by a sinking movement and results in diffusion of weight." *Weight transfer* is defined as: "A movement of weight to one ski."

In subsequent ATS manuals, the issues of weighting, un-weighting and weight transfer have been dealt with as part of "pressure control", which has been defined as: "The action of actively adjusting the pressure exerted by the skis against the snow (supporting surface). This includes such mechanisms as shifting pressure from one ski to the other (weight transfer), applying pressure to the front, back, or middle of the skis (leverage), and adjusting the magnitude of the pressure by vertical movements of the body mass (unweighting, absorbing, pressuring)."

So what is the problem and why do exam candidates (and many experienced, certified instructors for that matter) continue to have difficulties with these terms and concepts? Why is there confusion about what is actually going on? I suggest that the reason is that we have been using the wrong words to describe what is going on. The terms "weighting, un-weighting, weight transfer, weightless, etc." are all being used to describe something entirely different than *weight*. The words in themselves are fallacious.

In our physical world, weight never changes. Your weight is after all the product of your mass and the attraction due to gravity, both of which are constant (at least between meals!). So unless you have figured out how to turn off gravity or your mass suddenly becomes zero, you can never be "weightless", even if you are floating around in orbit in space. So to speak about increasing or decreasing weight doesn't make sense. A further problem enters because we have no means of sensing our weight directly. Our bodies do not have a direct weight sensing mechanism. This by the way is why the astronaut in space feels weightless. Remember our discussion of reference frames and in what reference frame on senses what is going on. The person in space senses dynamics in a moving reference frame attached to his or her body and in this frame the force of attraction due to gravity is exactly cancelled by the centrifugal force due to the orbital motion. The result is a perception of being “weightless”.

So instead of weight, what we do sense, whether just standing still on the bathroom scales or moving on a pair of skis, is the reaction force between our bodies and whatever is supporting them. So when we step on the bathroom scales, they only read out the magnitude of the reaction forces to our weight exerted by the springs or whatever other means the engineer designed as the working mechanism of the scales. Your sense of the pressure between your feet and the scales exists, but does not serve to measure your weight. You read the calibrated dial for that information. In the same way, the pressure you feel when you sit in a chair is evidence that your weight exists and that the chair is pressing back at you with a reaction force equal and opposite to your weight, just enough to keep you from falling. However, this does not give you a measure of your weight. Those who have jumped out of airplanes sky diving can identify with this lack of sensation. Your weight is still whatever it is, but in free fall, your senses have no information about it. This is an extreme example of the reaction forces to your weight being zero, and of course is the reason you are falling. This absence of sensation is often described as being "weightless", but you are not actually weightless.

Thus far I have not brought motion into the discussion directly (other than the free fall illustration). Let us now see what motion has to do with the business of "weighting", "unweighting" and "weightlessness". We can explore the effects of motion by doing some simple experiments on the bathroom scales. Provided of course that you can find an old fashioned, non-digital set of scales! The new digital read-out scales will not respond with a reading until you stand still for a while, then they read out your weight. They are constructed so as *not* to respond to the effects of acceleration! If you get on them and immediately start to move up and down, they never register anything, conversely, when you start moving after they have decided what your weight is, they never change no matter how you move. The benefits of the modern digital world. Anyway, supposing you are able to find an old fashioned spring scale with a dial, you can carry out the following experiments.

When you stand still, the scale reads your weight, and we know from Newton's First law that this is really the measure of the reaction force in the scale to your weight: The action is your weight and the reaction is the force exerted by the springs in the scales. Then drop suddenly and have a friend observe the reading on the scales. As long as you are dropping (accelerating downward) the scale reads less than your weight. This is as it should be since to accelerate downward, the resultant of the force of gravity acting down must be greater than the force exerted by the springs of the scale acting upward. Put another way, the scale needs to exert less pressure than your weight because it doesn't have to keep you from moving downwards. Unfortunately, this moment is brief indeed as you cannot "fall" very far! When you tense your muscles and stop your body from dropping, the scale will momentarily register a reaction force greater than your weight. The reason is that now the springs in the scale are *decelerating* you (stopping your body from falling) and this requires force greater than just the weight. The reaction force must equal your weight plus the mass times acceleration part, which is now in the opposite direction. As soon as you have stopped moving, the reading on the scales returns to your weight because the acceleration now is zero. Change the rate at which you perform these movements and observe the changes in the scale readings as part of your experimentation.

Now, extend upward from the scale (since this is an old scale, you can even jump). As you *start* upward, the reading first increases and then decreases, reaching a minimum at the top of your extension (zero if you actually jump up off the scale). Of course, gravity being what it is, you must return to earth. The scale reading will increase beyond your weight as it stops your fall, then returns to the weight value after motion stops. Again, to initially start you upward, the scale must exert a pressure greater than your weight (cause you to accelerate upward). Once you are moving, it registers less than the weight according to Law 2. It is difficult to think of the scale exerting the pressure to accelerate you upward. It really is a consequence of what you do with your muscles. But what actually allows you to accelerate upwards is the ability of the scale to provide the necessary reaction to your movements, the relative stiffness of the spring in the scale.

This situation is entirely analogous to the amount of "rebound" you get from your skis on hard snow versus powder.

The key here is that unless you are moving *and accelerating or decelerating*, the reaction force is determined only by your weight. The pressure on your skis will be constant, *until* you either accelerate the body away from the snow surface supporting your skis or toward it. As your experiments should show you, when you flex and extend at different rates (fast or slow), the magnitude of the reaction force will change. It doesn't matter whether the movement is a flexion ("down" movement) or an extension ("up" movement). Both will give rise to a (small!) interval of time when the pressure on the skis will be decreased from what it would be if you just stood rigidly on them (assuming that the slope is constant of course!). In straight running, these movements are perpendicular to the slope because your acceleration is strictly down the hill and the only components of your acceleration are perpendicular to the slope as well as along the slope. The pressure your skis feel is the reaction to the component of your weight perpendicular to the slope as well as any component of acceleration perpendicular to the slope, so any flexion/extension movements need to be in the same direction.

Now, in a turn, the acceleration will also have a component parallel to the slope *and* toward the center of your turn - the centripetal acceleration. The pressure on your skis will be reacting to both the components of weight perpendicular to the slope as well as the effect of centripetal acceleration (remember, your skis will have to be on edge to turn). To put it another way, the direction of the ski/snow reaction force will no longer be either perpendicular to the snow surface nor along the line of gravity (the direction your weight acts). So if you wish to most effectively change the pressure between your skis and the snow, your flexion/extension movements will have to be perpendicular to your skis, since they are no longer flat to the snow nor perpendicular to true vertical (the line of action of gravity). Thus your flexion/extension movements will have components both perpendicular *and* parallel to the slope. And in fact, the movement parallel to the slope will be to the inside of your turn.

The key is to keep in mind that what we are concerned with is *not* weight, which *always* acts along true vertical and remains constant, but the pressure that the skis experience from the snow. This pressure is what we are talking about when we loosely use the terms "weighting", "un-weighting" and so on. "Weight shift" thus really means how we manage the pressure distribution from one ski to the other. This is accomplished by arranging where our feet are in relationship to our center of mass. "Weight shift" then is a conscious decision of how much of the reaction burden to weight and the effects of acceleration should one ski or the other carry.

We can continue to use the terms "weighting", "un-weighting" and "weight shift" if we wish. However, we should have a clear understanding that what we are *really* talking about are the reaction forces between the skis and the snow or pressure control. And these forces react to both weight (a constant) and the effects of the body acceleration, usually not constant, nor aligned with true vertical. This body acceleration can be the result of what the terrain does to us or of what we actively do with our bodies. Part of this pressure control thus is the result of flexing, extending and various combinations thereof in whatever direction we choose. Some directions are more effective than others, depending on the dynamics of the moment.

Discussions of “unweighting” often enter arguments about what mechanisms are more effective for turn initiation as well. Is “up unweighting” more effective than “down unweighting”? What is the total time during which the pressure on the skis is decreased for each set of movements? Is the time of decreased pressure during the down movement sufficient to execute other significant movements? For these discussions, we need to keep in mind that to turn skis, *all* components of the ski/snow interactions must be considered. The pressure (with resultant normal force)is certainly one, but lateral forces due to edging or other causes need to be taken into account as well. For example, when skiing crud, the primary concern is to get the skis out of the snow to turn them, not because we are seeking "unweighting" but because there is too much lateral resistance from the snow to turn. The "up" or"down" movements used for "unweighting" often do more to change edge angles and the resistance of the body to existing turning forces than they change the pressure on the skis. The point here is that we need to consider all aspects of what is happening at the ski/snow interface. Different conditions will require different body movements. Often more than one class of movements will yield the same result, but one particular set of movements may be prefered by the skier. Such issues as effectiveness, efficiency as well as aesthetics will determine specific choices.

Two additional concepts often create difficulties and need to be clarified: angulation and inclination. These terms are well-entrenched in ski technical jargon but still create confusion. I define angulation as the creation of angles between major body segments, thus the head and arms are not (directly) involved. Angles created between the longitudinal axes of the trunk and the thighs ("hip angulation"), angles created between the thighs and lower legs (so called "knee angulation") and combinations of the two are the results of "angulation". In addition, the upper torso may or may not have a twisted relationship to the hips. A typical angulated position involving both the knees and the waist is shown on Figure 6.1.

Inclination is best defined as the angle between the longitudinal (head to feet) axis of the body and vertical as defined by the line of action of gravity. I need to introduce an additional reference line since most often inclination exists simultaneously with angulation. This reference line is the line of action of the resultant of the ski/snow reaction forces. Recall that if this resultant acts through the center of mass, the body will be in equilibrium, no matter what the body configuration is. So inclination is the angle between vertical and this line of action of the ski/snow reaction forces. For ease of visualization, we can think of this line as a line drawn from the inside edge of the ski to the center of mass. This of course is not strictly true if both skis are pressured, since in that case the resultant line of action lies somewhere between the two skis. A typical inclined position (with minimal angulation) is shown on Figure 6.1 for both a relatively slow turn (hence minimal inclination) and a fast one (more inclination).

It is important to emphasize that an inclined position *without* angulation is not necessarily out of balance. Balance requires that the resultant of the ski/snow reaction forces passes through the center of mass, and that is all. The actual configuration the body assumes and how much angulation is combined with inclination will depend upon many factors. For example, speed, radius of turn, steepness of the slope, the skier's strength, individual anatomical features and alignment all combine to determine how the skier will arrange the body to manage the forces involved. As discussed in chapter 8, efficiency and effectiveness are increased with proper alignment, thus removing the need for certain body positions that are often assumed to ensure that the skier remains in balance, i.e. equilibrium.

In closing this brief section on misconceptions in mechanics, I would like to offer some words of caution to those tempted to apply the concepts of classical mechanics to the analysis of skiing. The motions we are analyzing are very complex. The moving system is an interconnected set of flexible bodies of finite dimensions, the actuators (control effectors that create movement) are themselves distributed and flexible, the sensors (that sense movement) are poorly understood as are the control mechanisms that are used. The environment in which the motion is to take place is also highly variable and thus the nature of interactions of the system whose motion we are trying to understand with the environment is poorly defined as well. Application of simple models and simple abstractions to draw conclusions should therefore be done with great care. We are not dealing with simple physics applications here and models that only capture the bare essentials of the Newtonian laws for particle dynamics can and do lead to erroneous conclusions. This is particularly true if one attempts to generalize the conclusions based on the simple models.

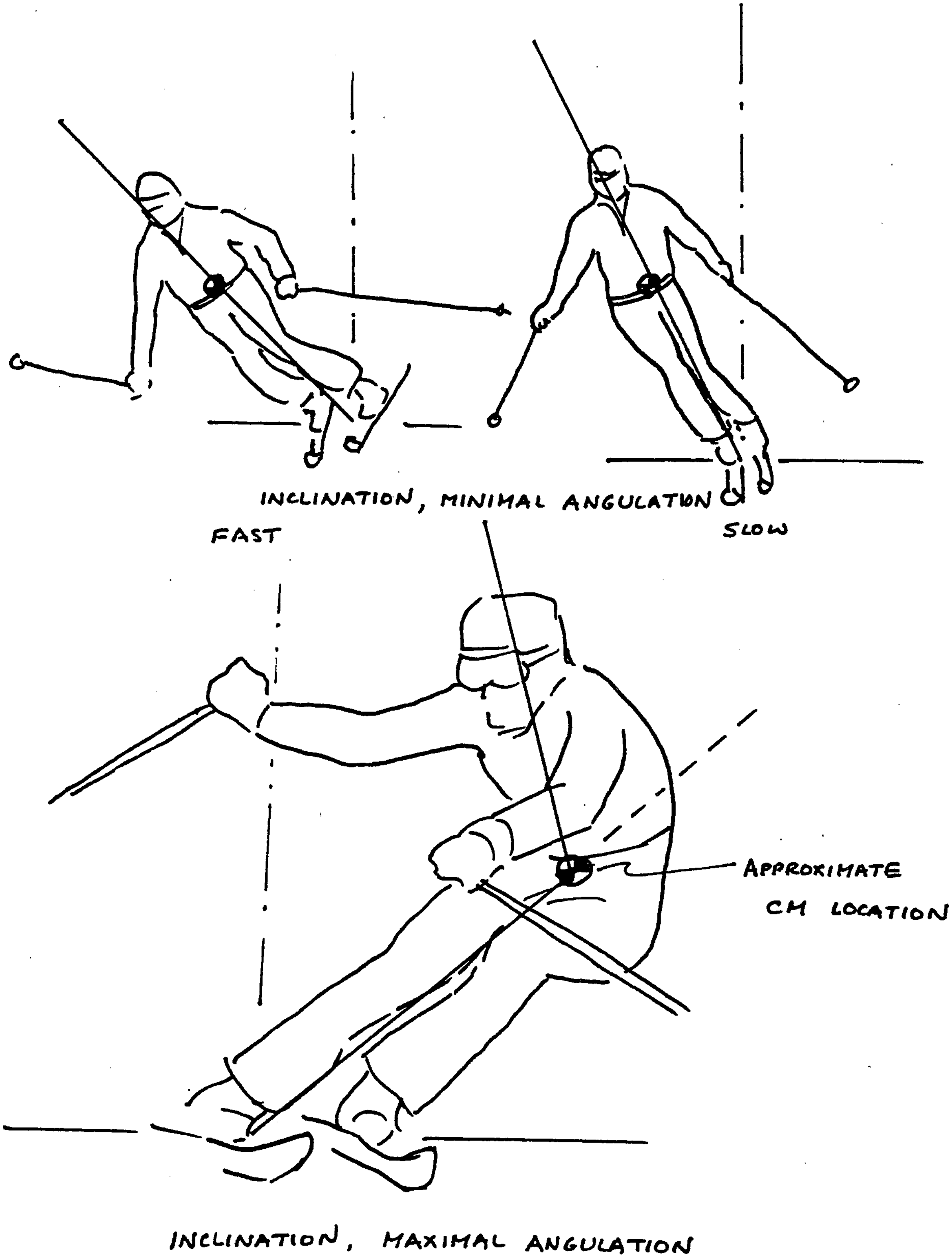


FIGURE 6.1 INCLINATION AND ANGULATION

7. THE VOCABULARY AND CONCEPTS OF BIOMECHANICS

7.1 ELEMENTS OF ANATOMY

The two principal anatomical systems of concern to the student of human motion are the skeletal and skeletal muscle systems. Clearly a complete treatment of the characteristics of each of these systems is not in the scope of this discussion, however, one should have a clear understanding of at least the key elements of each. Thus we are concerned with that function of the skeletal system which provides levers and joints for body movement and with the lower extremities in particular. Body movements are the result of skeletal muscle action; due to the involvement of more muscle groups in complex body movements than just the muscles of the lower extremities, the understanding of the skeletal muscle system must be correspondingly greater. The interaction of the skeletal and skeletal muscle systems occurs when muscles act (apply force) through connective tissue (tendons) to levers (bones) causing motion of bones relative to one another by moving the levers around a fulcrum (joint) provided the force is great enough to overcome the resistance to motion against the lever. Muscle action can take several forms, as will be explained in section 7.1.2 below.

The specialist in biomechanics will find that quite a number of "fine points" are not included in this brief introduction. For example, each of the following subsections can occupy an entire textbook, and even that should be supplemented with current research results from scientific journals. This situation is in contrast to the material on mechanics: the fundamental concepts and laws can be put down quite succinctly. The rest of the story in mechanics textbooks is simply application of the basic results to a variety of problems.

7.1.1 THE SKELETAL SYSTEM

The key bones and joints of the lower skeleton are shown in Figure 7.1. The principal lower extremity joints used in skiing are the hip, knee and ankle joints. Movement to some degree occurs in the joints of the foot. For alpine skiing, the effects of foot joint motions are of importance when we consider body alignment and load transfer to the boot/binding/ski system. The foot structure is very flexible and there are significant deformations under loads that influence how the loads are transferred through the foot structure. This flexibility is the reason that foot beds and orthotics play such a significant role in skiing mechanics.

To understand and correctly identify the mechanics of movement, we must know the different types of motion of joints, the directions of possible muscle forces across joints and the restrictive effects of ligaments bridging the joints. Recall that from a mechanics point of view, the muscles and limbs are the control effectors that we use in controlling motion. Thus, some understanding of the structure and action of these effectors will help in reasoning about effectiveness and efficiency of movements.

In general, the joints of the lower extremities are capable of the following types of motion:

Flexion: Movement of contributing members or segments toward each other

Extension: Movement of contributing segments away from each other; motion beyond the normal extended position is called hyperextension

Abduction: Motion away from the central (spinal) axis of the body

Adduction: Motion toward the central axis

Circumduction: Rotation about the long axis of the contributing member moving with respect to a single pivot point.

The hip joint is a ball and socket joint and hence capable of all types of motion restricted only by the surrounding structure and flexibility of muscles and ligaments. From Figure 7.1 it can be seen that the ball portion is the proximal end of the femur or thigh bone which fits into the cup-like socket of the ilium or "hip bone" In modern advanced skiing, the mobility of the hip joint is critical.

More complicated motion is possible in compound structures such as the ankle joint (talocrural joint). The bones involved are the tibia, fibula and the talus. This hinge joint allows dorsiflexion (decrease of the angle between the tibia and the plane of the foot or sole) and plantar flexion (increase of that angle) as well as a slight amount of rotation. Dorsiflexion is restricted to fifteen degrees or so while plantar flexion is possible up to approximately forty five degrees. Eversion (tipping of the feet sideways so as to form a V with the soles) and inversion (tipping of the feet so as to form a Λ with the soles) are examples of the complex motions possible with the ankles and feet. The structure of the foot and ankle is illustrated on Figure 7.2.

The knee joint is a hinge-type joint (details shown in Figure 7.1) and hence capable of more restricted types of motion. The knob like protuberances at the lower end of the femur (thigh bone) fit into the plateau-like end surface of the tibia (lower leg). This structure allows flexion and extension, slight rotation (maximum of 25 degrees), but only when the knee is flexed at approximately 90 degrees, and minimal motion in abduction and adduction without injury to the supporting structure. The range of rotation is usually considered to increase as the knee approaches 90 degrees flexion and then decrease again during extension.

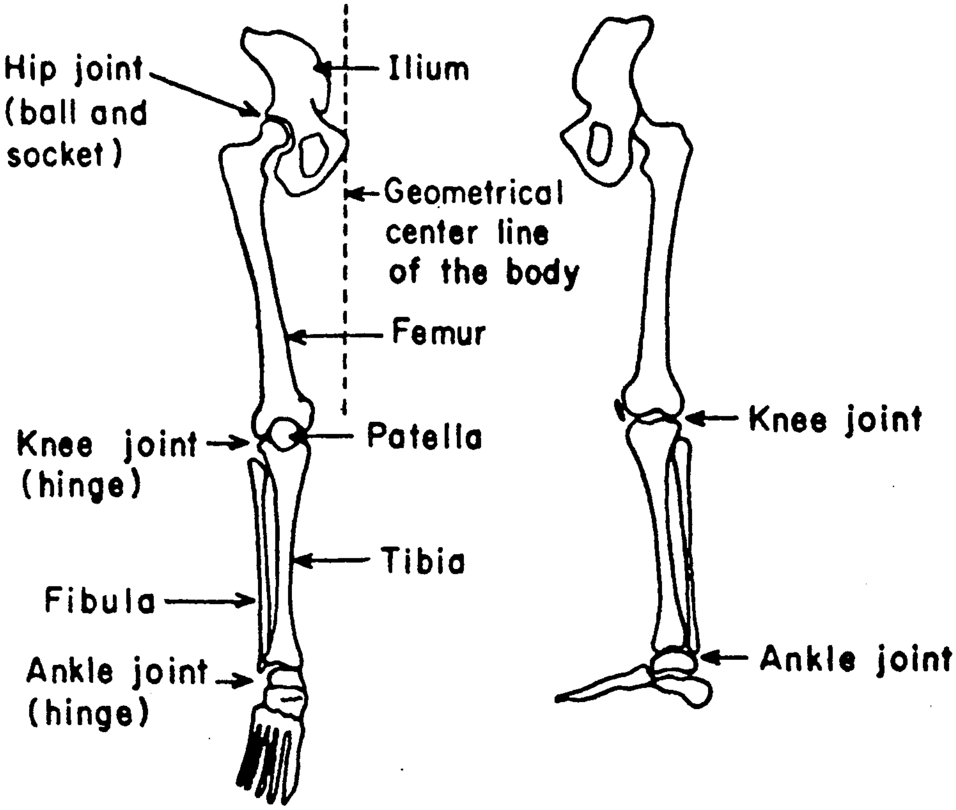
The ankle joint is also a hinge-type joint and hence capable of flexion and extension only. Rotation or circumduction is not possible in this joint without injury. All motions of the ankle joint are severely affected by the stiffness and structure of the boot.

Of the remainder of the skeletal system, the structure of the trunk is most significant for skiing movement analysis. The bone structure of the trunk includes the spinal column, the bones of the rib cage and the bones of the pelvic region. All trunk motor movements (excluding breathing) involve movement of the spine. The structure of the spinal vertebrae and the sponge like discs that separate them allows a small amount of movement in any direction between each pair of vertebrae. Combined movement of all vertebrae results in extensive movements of the upper trunk relative to the lower or pelvic segment.

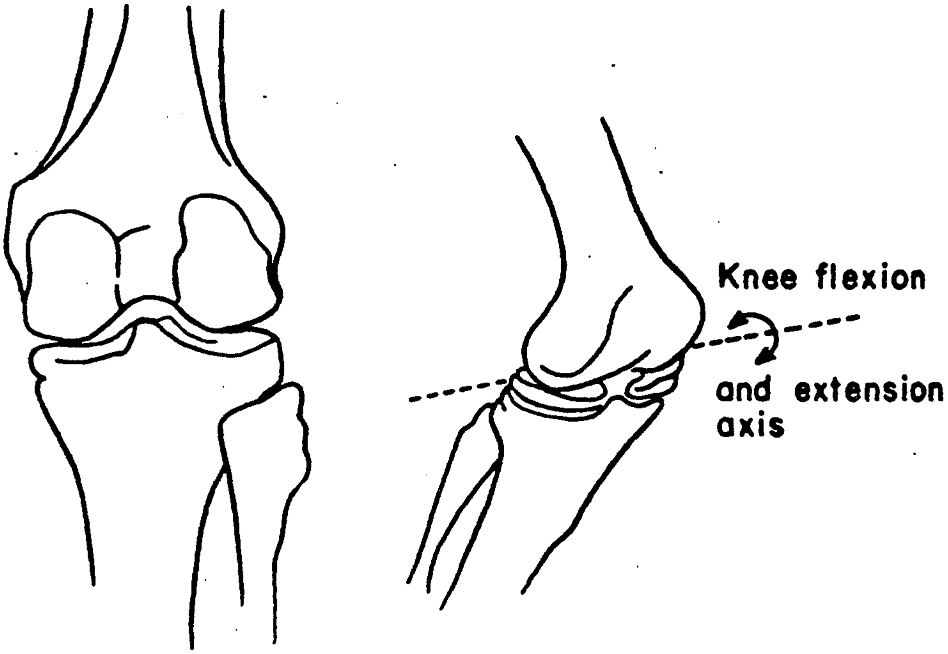
7.1.2 THE MUSCULAR SYSTEM

The major muscle functions for kinesiologic analysis of skiing are: 1) To counteract the effects of gravity and other external forces to maintain desired body alignment and attitude and 2) to realign body segments in the execution of movements, thus influencing how the effects of external forces are transmitted to the body center of mass.

A muscle can only act or relax, and under normal conditions, action results only from nerve impulses. Generally, when a muscle acts to contract (shorten) its length,



FRONT VIEW INSIDE VIEW



DETAILS OF KNEE JOINT

FIGURE 7.1 THE BONES AND JOINTS OF THE LOWER EXTREMITIES

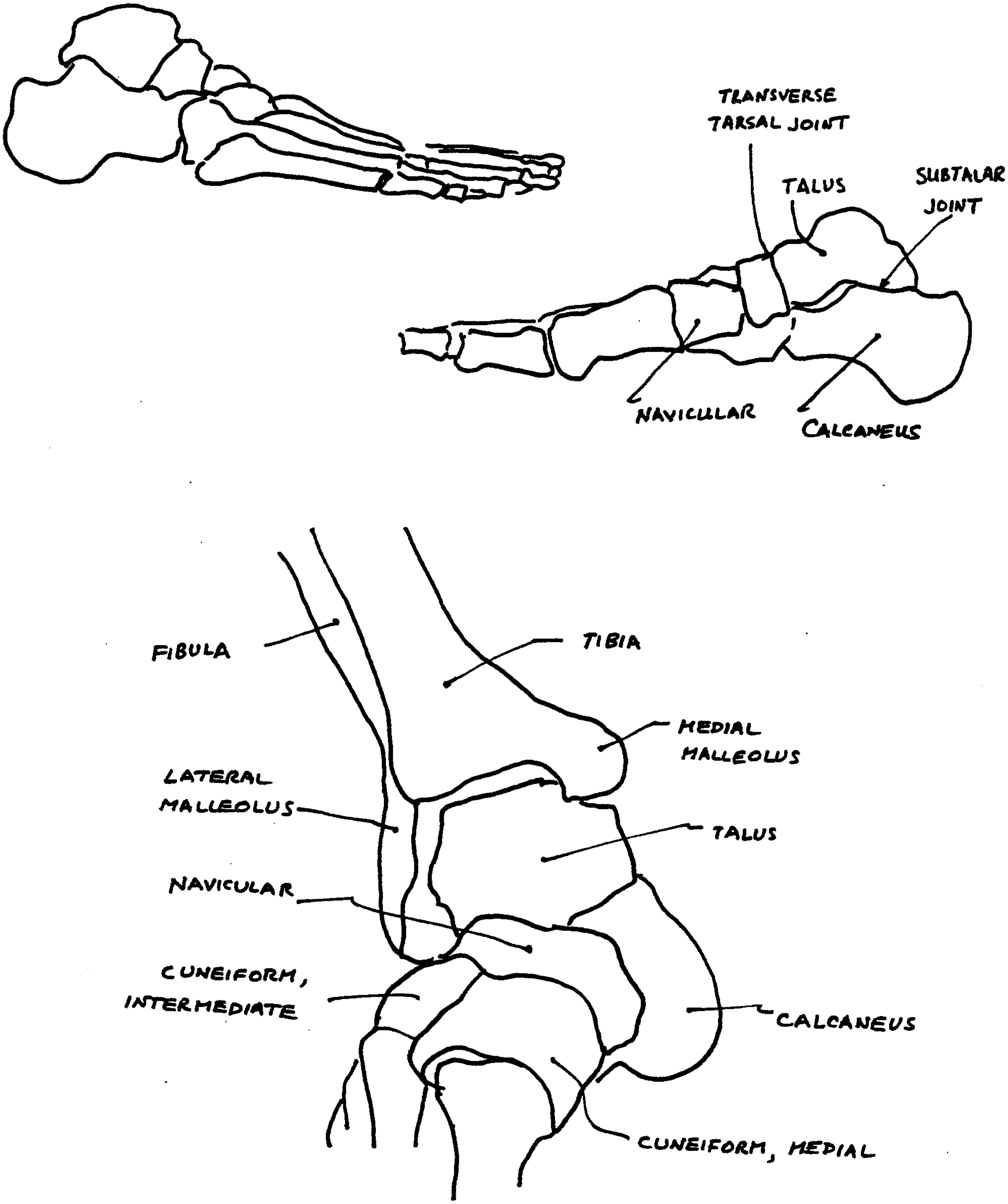


FIGURE 7.2 STRUCTURE OF THE FOOT AND ANKLE

contraction occurs from the center of the muscle i.e.. the muscle pulls the attachment bone segments toward each other. Which segment moves depends on the relative stability of the segments. The stability is determined by mass, bracing or the action of stabilizing muscles. Muscles only rarely work alone, rather, muscle groups are involved to achieve any given joint action.

There are three forms of muscle action: a) isometric, where tension is developed in the muscle but no change in length takes place in the acting muscle, b) concentric contraction, when shortening occurs when the muscle acts, and c) eccentric contraction, when lengthening occurs. These different types of muscle action are experienced when a person holds a weight in his or her hand. If the elbow is flexed from extended position to 90 degrees, we have concentric contraction of the elbow flexor, if the weight is held steady in the 90 degree position, we have isometric action and if the weight becomes too great and is slowly lowered due to pull of gravity (or just lowered intentionally), we have eccentric contraction of the elbow flexor. This situation arises any time when the external force acting is greater than the internal force the muscle generates.

In performing movements, the controlled variables are speed, force and duration of the muscle actions in reaction to stimuli. The relative importance of these variables, depends on the type of movement to be performed. Thus one has maximum force movements, where the prime mover muscles act at near-maximum force and speed either continuously or for brief periods of time. The "length-tension" relationship demonstrates that a muscle generates maximum force when it is at approximately 1.1 to 1.2 times its resting length. Speed of movement is a function of both contracting power as well as the ability to completely relax muscle groups opposing the movement. Because muscular action spans joints connecting limb segments, there are some lever-arm joint angles that are more advantageous and for which muscles operate more effectively.

If one uses brief, powerful explosive muscle contractions, they usually serve to set a body segment into rapid motion, termed a ballistic motion. In ballistic motion, after the muscle contraction stops, the velocity of the movement gradually is reduced due to internal resistance in the joints, resistance of muscles opposing (antagonistic) to the movement and external resistance. To stop such movements at the desired time, the antagonistic muscles must contract eccentrically. In modern advanced skiing, rapid reversal of ballistic movements is often required. Recent research has also shown that maximal force contraction for extended periods of time also occurs in skiing and often must exist in a disturbance environment, i.e. with severe vibrations going on.

Two modes of action for muscles have been identified: 1) As prime movers (agonist) and 2) as antagonists or opposing forces. Since muscles work in groups, production of a specific desired movement will require some muscles to act as prime movers, others to relax to their greatest extent (minimize resistance) and others to act as antagonists, to neutralize certain effects of the prime movers. This course of events is necessary since a contracting muscle will cause all the movements in a given joint of which it is capable, but not all of these movements will be desirable. A further function of muscle groups is to stabilize a joint during certain phases of movement to prevent undesired motion or injury to the joint.

I have used the term "stabilization" here to mean stabilization as a result of continuous muscle action, not just the prolonged isometric contraction of muscles surrounding a joint to immobilize it. By stabilization I mean brief, instantaneous muscle contraction to accomplish three purposes: 1) To maintain the position of the body against gravity, other external forces and the internal forces generated by muscle contractions during a desired movement 2) To prevent injury to joints and surrounding tissue during movement, particularly ballistic movement and 3) To provide a base from which internal forces may be transferred from one part or segment of the body to another during the execution of a sequence of movements.

Injury to joints is primarily prevented through muscle action, not because of ligaments. Also, injury may occur as a result of static loading or dynamic loading during movement. Therefore it is clear that the best insurance against joint injury is to maintain the muscles of the lower extremities at their peak condition.

The controlled ballistic movements possible under stabilization due to continuous, low level or intensity muscular actions provide the human mechanism a possibility of conserving energy. Without this capability an individual would not be able to sustain muscular activity for long periods of time. The more skilled the athlete, the more he or she is able to use "periods of relaxation" during different phases of motion, thus conserving energy. This increase in efficiency is realized in addition to what is gained by using more efficient body skeletal alignment and body movements overall.

The details of muscular activity are quite complex. To be effective, all movement from slow to ballistic must be guided, for which purpose certain muscle groups will serve as "balancers" of the prime mover muscle effects. Thus we see the complex actions which must occur in muscle groups affecting any joint in motion or under isometric load: *prime mover contraction, antagonistic inhibition, dynamic stabilization and guidance.* During a particular movement, individual muscles may act in any or all of these capacities. The smoothness, speed and efficiency - what is called coordination - of the aggregate muscle group action depends on the training for the particular movement as well as qualities peculiar to each individual.

So far I have spoken of muscle groups acting across a single joint. There are also muscles which extend across more than one joint and hence contribute to the motion of each joint they cross. For example, the hamstring group, located in the back of the thigh, crosses the hip and knee joints and can be used to cause the knee to flex and the hip to extend upon contraction. Similarly, the rectus femoris across the front of the thigh can extend the knee and flex the hip. A characteristic of such multi-joint muscles is that they do not allow complete range of motion at one time in all the joints they cross unless exceptional effort has been devoted to increasing their flexibility. Of the twenty muscles surrounding the hip - some of the largest and most powerful muscles in the body - six cross the knee joint. For this reason, flexibility of all lower body muscle groups is highly desirable for efficient skiing and in fact, mandatory for some of the more advanced movements of modern ski technique. In this context, I note that flexibility is specific to each joint. The left and right limb muscles may be significantly different in flexibility unless exercises are carefully balanced to insure against such "one sidedness".

The levels of muscular activity during skiing have been the focus of numerous studies, reported in the sports science literature (see References 13 -16). The primary means of studying muscle activity while skiing has been the use of telemetry with electromyography (EMG). EMG typically involves the placement of electrodes on the subjects' skin over the specific muscle group of interest in the investigation. To establish a reference level for muscle activity assessment, the subjects are tested first in the laboratory. During these laboratory tests, proper electrode placement is verified by specific manual muscle testing. Then, specific tests are conducted to establish maximum voluntary muscle contraction (MVC). These tests are done both before and after the on-slope data are collected. In this fashion, the relative activity levels of different muscle groups can be related to a common reference basis, i.e. the isometric MVC recorded for each group. Some of the studies attempt to correlate the muscle activity with other data as well e.g. joint movement angles measured with various devices, ski loading or binding forces, and qualitative assessment of turn characteristics. In contrast to the EMG data, there is some ambiguity regarding the definitions of such qualitative events as turn initiation, turning, turn completion. Thus, care must be exercised in drawing conclusions about specific muscle use for the different phases of a turn, for example, but conclusions about the involvement of different muscle groups can easily be correlated between studies. As shown by Hintermeister, et. al. it is important to include as many of the muscle groups as feasible in the studies, since a high level of EMG activity was noted in all the muscles (12 groups in their study). If one only has results for some isolated group and there is evidence of a high level of activity, one cannot automatically conclude that the specific muscle studied is the major contributor in skiing.

Understanding of specific muscular involvement in skiing provides a guide to training and conditioning activities. For the technical coach, this knowledge also provides another tool for diagnosis of performance problem causes that may be linked to specific physical limitations. A deeper understanding of how muscles act helps the instructor to evaluate the specificity of different exercises. To gain this understanding, read the referenced literature.

To aid you in reading the technical literature, the musculature of the lower extremities and trunk is illustrated on Figures 7.3 through 7.5. On these Figures the major muscle groups that have been observed to be active in skiing have been identified.

7.1.3 MUSCULAR ACTIONS OF THE TRUNK AND LOWER EXTREMITIES

To communicate effectively when discussing movements of the body, we must establish axes of reference relative to the body. The three principal axes will be called the longitudinal (head to feet), lateral (right to left) and transverse (front to back) axes and are shown in Figure 7.6. Traditional anatomical literature also introduces three principal planes of motion: 1) The sagittal (anteroposterior) plane, dividing the body into right and left, 2) the lateral (frontal) plane, dividing the body into front and back, and 3) the transverse (horizontal) plane, dividing the body into upper and lower segments. The relationship of the axes and planes is shown in Figure 7.6. Note that both reference axes and planes are established relative to the normal standing position of the body, however, this does not imply reference relative to vertical.

Movements (rotations) about the longitudinal axis take place parallel to the transverse plane, movements (rotations) about the lateral axis take place parallel to the sagittal plane and movements (rotations) about the transverse axis take place parallel to the lateral plane. This slightly confusing convention is well established in kinesiology literature and hence is also used here. The movements may involve limb segments, total limbs, segments of the main body, the entire body or any combination thereof. If this specific terminology is confusing, simply referring to movements in the front-rear, or side-to-side planes will be accurate enough for most discussions.

7.1.4 MUSCULAR ACTIONS OF THE ANKLE AND THE KNEE

The major muscles of the lower leg are identified on Figure 7.3. In the study of Hintermeister, et.al. the anterior tibialis (AT) and the medial gastrocnemius (MG) were observed to be very active both in slalom and giant slalom turns. The authors note that the activity in the anterior tibialis corresponds to the stabilization of the foot and leg while changes in balancing and steering actions occur during the turn. The major muscles of the thigh are identified on Figure 7.4. The muscles participating in knee flexion are the

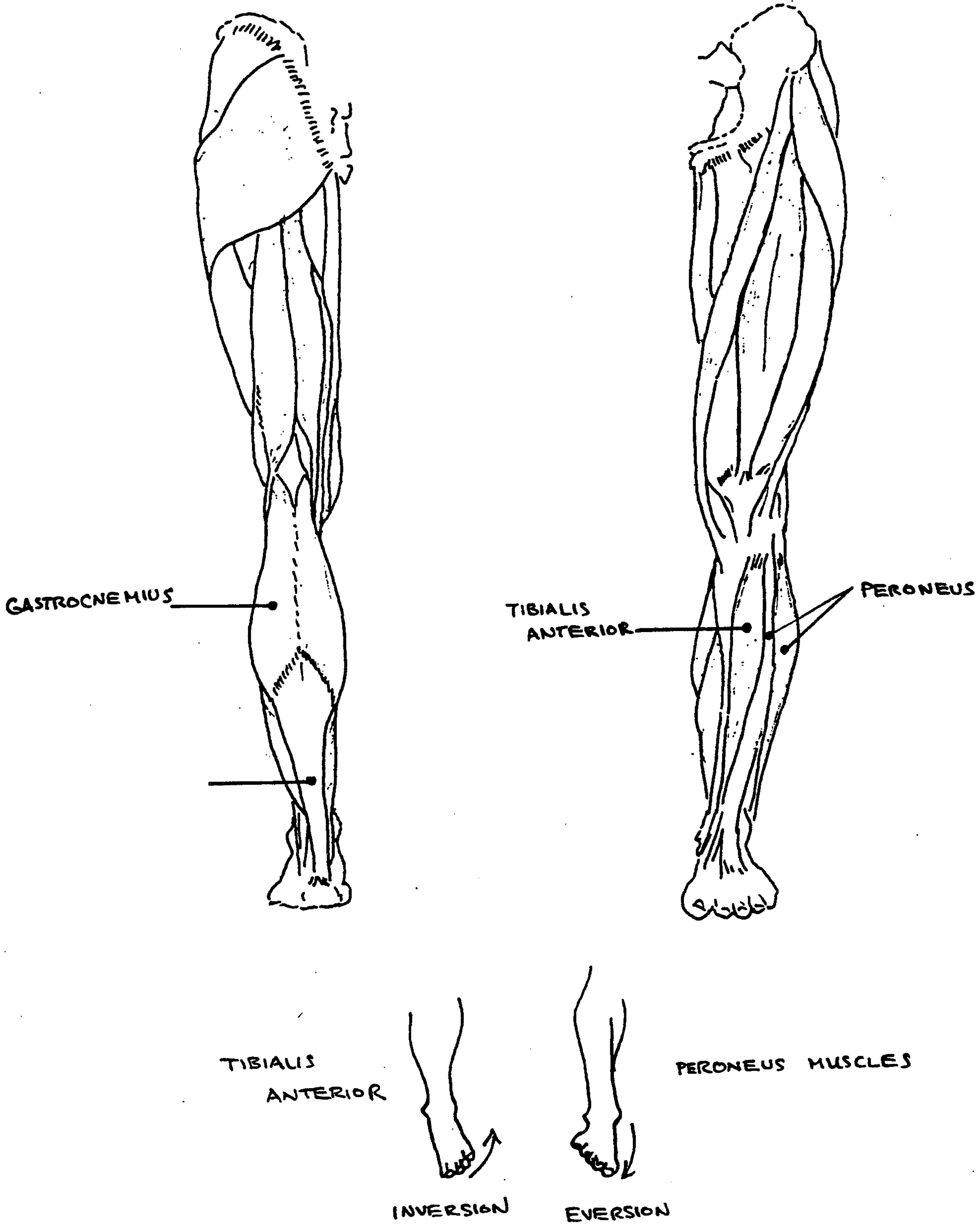


FIGURE 7.3 MAJOR MUSCLES OF THE LOWER LEG

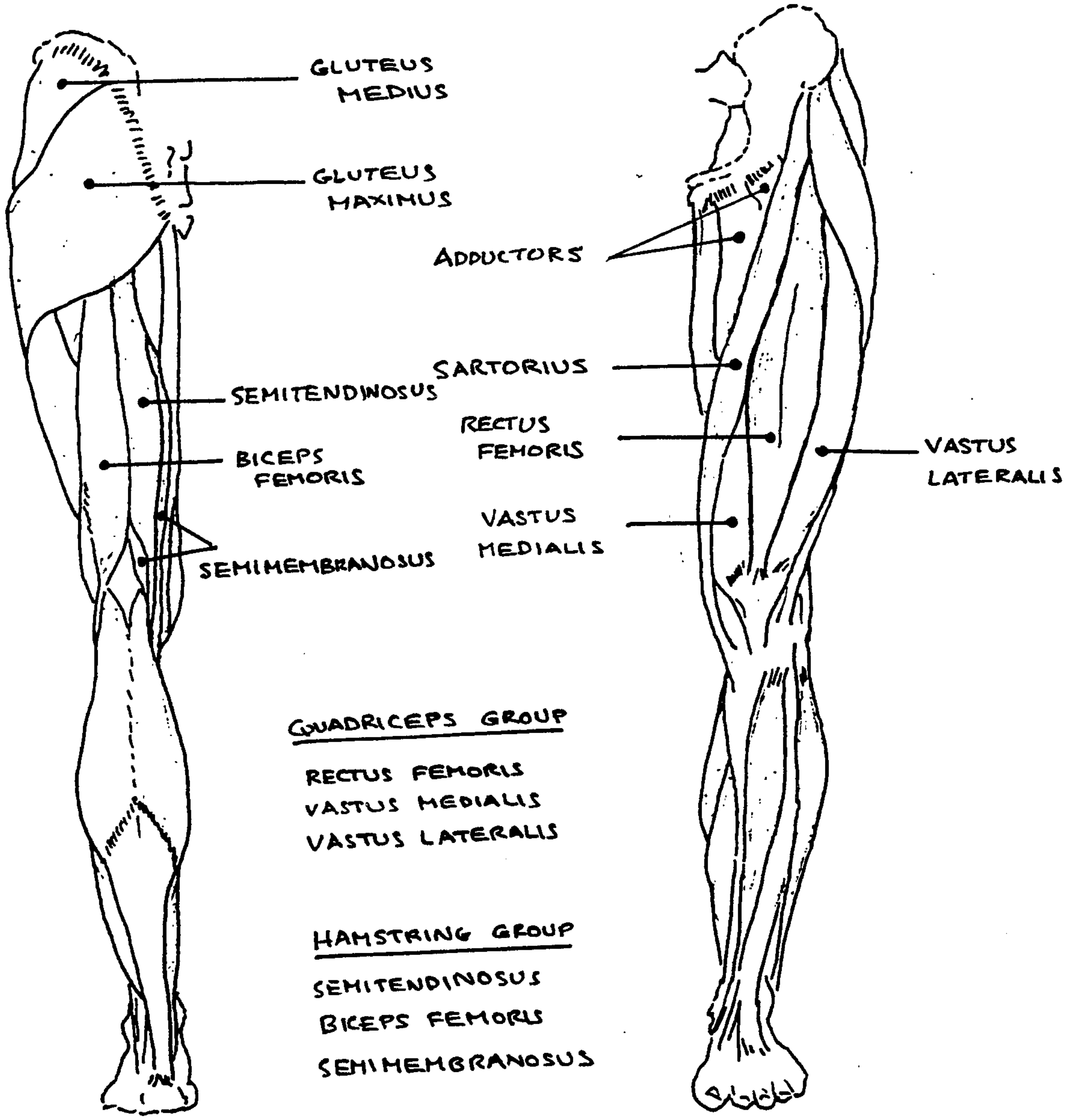


FIGURE 7.4 MAJOR MUSCLES OF THE THIGH

semitendinosus and the semimembranosus (the hamstrings). For knee extension, participating muscles are vastus medialis (VM), vastus lateralis (VL), rectus femoris (RF) and the biceps femoris (BF). All of the major thigh musculature was observed to be active by Hintermeister, et. al. The level of co-contraction along with the slow angular velocities of the knee during giant slalom suggest a quasistatic component to skiing and the significance of the thigh musculature for stabilizing action during skiing.

As noted in the section on the skeletal system, the ankle and knee joints are primarily capable of flexion and extension with minimal rotation. Introduction of high, inflexible ski boots further restricts the range of movement allowed for the ankle joint to slight flexion and extension parallel to the sagittal plane if no rotation takes place at the hip joint (or a flexed knee joint). Of these two movements, extension (plantar flexion) is a strong movement since the prime movers are the strong muscles of the calf and flexion (dorsiflexion) is a relatively weak movement. In skiing maneuvers, there is a substantial discrepancy in the average amplitudes of the activity of the dorsi and plantar flexors of the foot. The anterior tibialis and medial gastrocnemius control forces affecting the fore/aft distribution of pressure on the skis. The activity of the AT was substantially greater than that of the MG combined over all phases of the turn. This increased level is to be expected from the force distribution along the ski during turns, i.e. the AT must work against the torques generated from the forces acting on the ski ahead of the boot. The activity of both the AT and the MG muscles can be aided by gravity action pulling on the body depending on whether the center of mass is forward or back of the neutral position over the ankle. For example, when a skier moves the center of mass toward the tail of the ski, we have eccentric contraction of the dorsiflexors, tibialis anterior, etc. rather than plantar flexion involving the calf.

Immobilization of the ankle relative to the lower leg aids the stability of the ankle joint. The muscles surrounding the joint are required to be less active in dynamic stabilization. For example, the major muscle on the front of the lower leg (tibialis anterior) becomes less fatigued during a day of skiing, even though research has shown that this muscle is quite active in skiing. We recognize this fact by how sore it gets after the first few days of skiing, if pre season conditioning has neglected training the tibialis anterior. However, the loss of mobility and dynamic stabilization action of the muscles also results in loss of muscular "perception" or feel of lower leg forces. I shall return to this point later. Note, however, that all muscle action at the ankle joint is not eliminated. Ankle muscles are still involved, although almost isometrically, in distributing the lower leg forces to the foot such as to the inside or outside of the foot in edging and edge control movements. Everyone is also familiar with the phenomenon of "gripping with the toes" on the early runs of the day or when skiing icy or rough snow conditions, with the consequences of arch cramping and accompanying pain. To relieve the pain, the muscles of the foot and ankle must be relaxed through climbing or similar exercises.

The use of the knee is crucial in all skiing maneuvers. As seen from the discussion of its structure, the principal movements occur in flexion and extension parallel to the sagittal plane (fixed hip orientation) with rotation possible to a slight extent when the knee is flexed. Maximum rotation occurs only when the knee is flexed at 90 degrees with no rotation possible in the extended position. Twelve muscles contribute to the flexion and extension movements of the knee of which eight are two-joint muscles also acting on the hip flexion and extension or ankle dorsiflexion and plantar flexion. Thus, immobilization of the ankle will also affect the movements of the knee by modifying the behavior of the two muscles crossing both knee and ankle (gastrocnemius and plantaris). However, more important are the six two-joint muscles spanning the hip and knee joints. In addition to influencing knee flexion and extension, all the *prime mover muscles* involved in lower

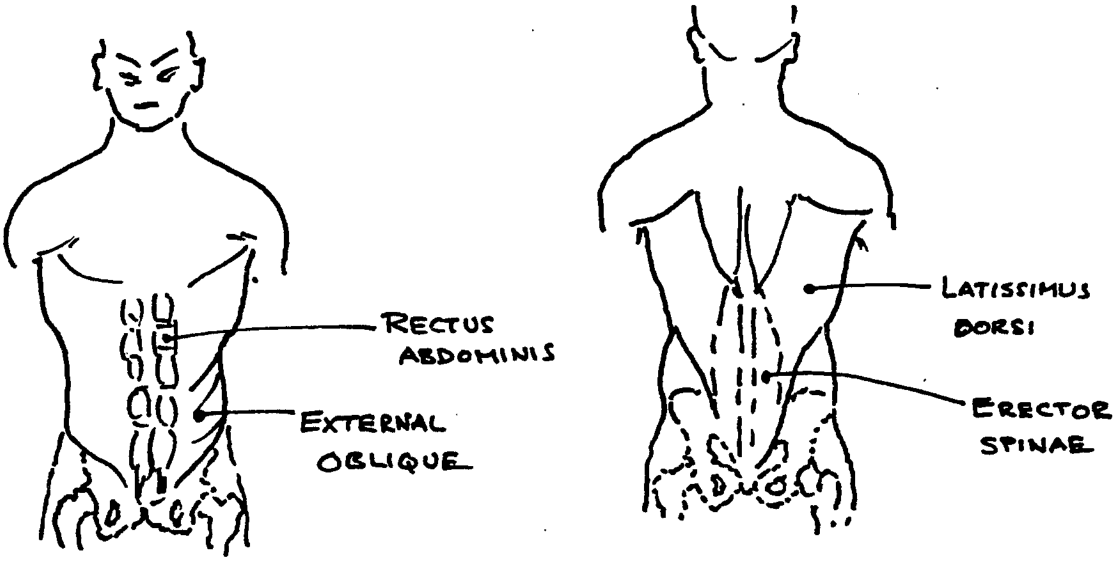


FIGURE 7.5 MAJOR MUSCLES OF THE TRUNK

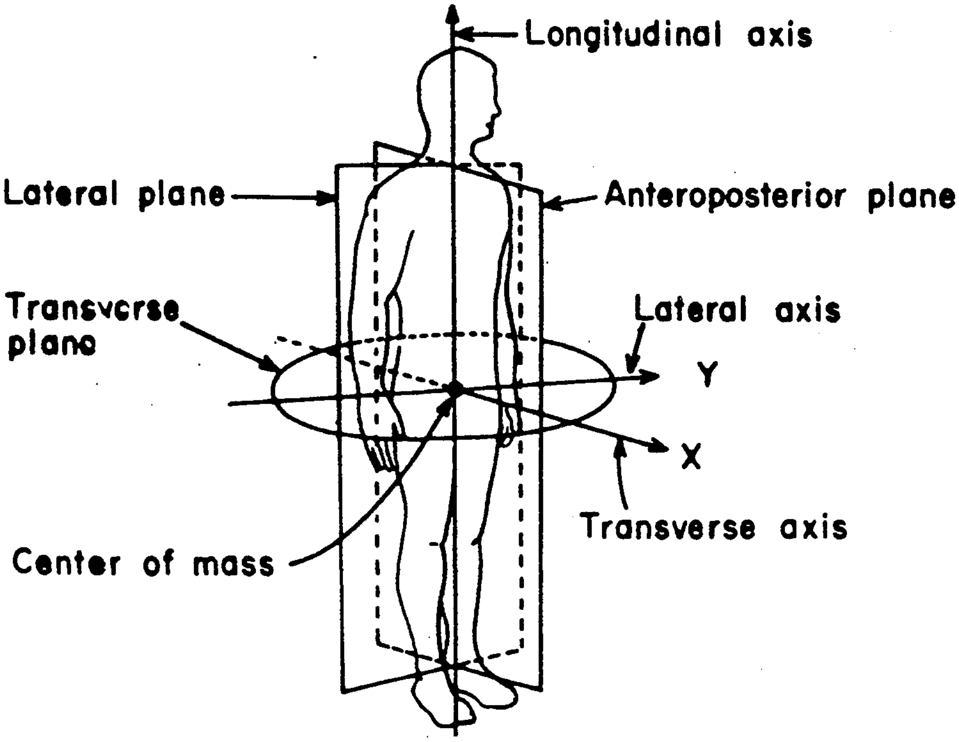
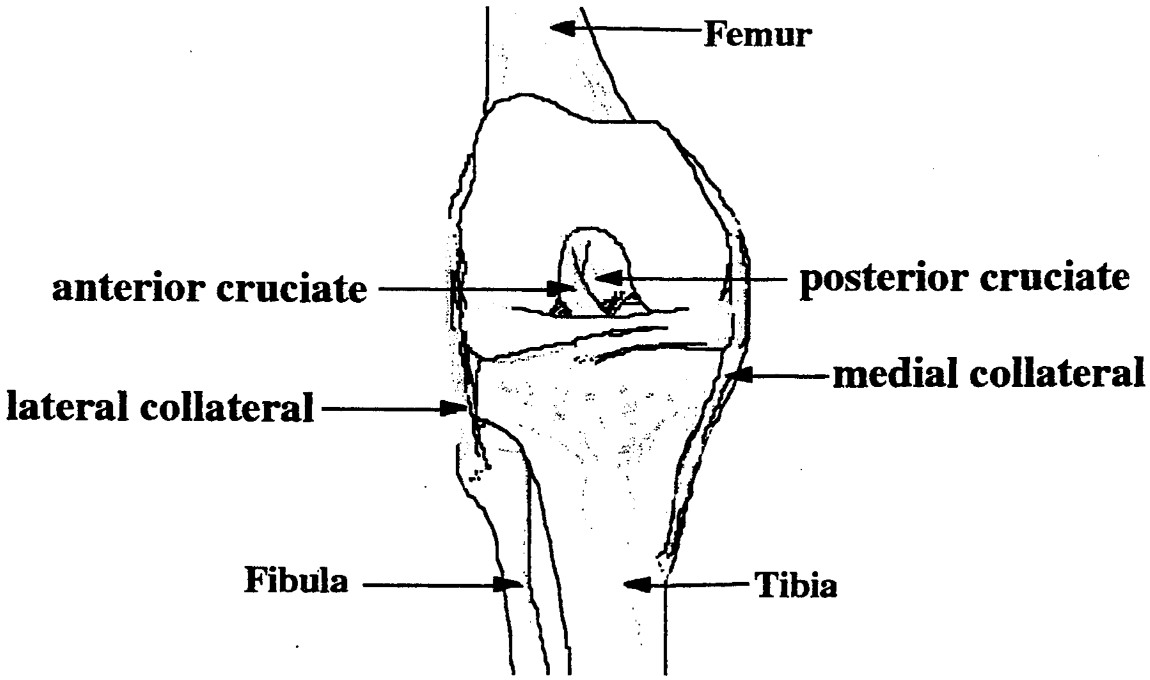


FIGURE 7.6 ANATOMICAL REFERENCE AXES AND PLANES

Knee Ligaments



(Note: Image courtesy of TechPool LifeART images and Steadman-Hawkins Foundation)

FIGURE 7.7 LIGAMENT STRUCTURE OF THE KNEE leg rotation also cross the hip joint, in fact, five of the six contributing muscles are hip-knee two-joint muscles Thus one cannot speak of knee and hip actions independently when discussing lower limb movements.

Finally, as noted earlier, muscles play a key role in preventing injuries to joints. One result of modern ski equipment evolution has been the transfer of injury sites. Anterior cruciate ligament (ACL) injuries are now very common, particularly for advanced to expert level skiers. The major ligaments of the knee are identified in Figure 7.7. Most ACL injuries occur when the skier's lower body is moved forward in relation to the upper body or the upper body moves backwards in relation to the lower body. This action displaces the distal head of the femur posterior to the tibial plateau. Since the ligamentous connection of the ACL connects the anterior spine of the tibia to the posterior part of the lateral condyle, the action described above puts the ACL under high tensile loads. High performance equipment can contribute to creating such motions because it is capable of creating significantly higher forces from ski/snow interaction.

When this relative fore-aft motion of the upper and lower body parts is combined with a twisting motion, the loaded ligament is subject to a shearing force. When the hamstrings are strong, the posterior displacement of the femur can be countered by a contraction of the hamstrings. This contraction pulls the proximal tibia (or keeps the proximal tibia) under the articular surface of the distal head of the femur. This keeps the ACL in a more optimal tension zone.

ACL injuries have been attributed to an imbalance of the quadriceps strength to the hamstring strength. There is reason to believe that the imbalance is the issue, not that the hamstrings are weak. Skiers have strong quadriceps, strengthened by training and skiing itself. The hamstrings are usually strong as well, but may be weak in comparison with the quadriceps. The details of what exactly is going on are complex and the subject of ongoing research. For now, don't forget the hamstrings in your conditioning program.

7.1.5 MUSCULAR ACTIONS OF THE HIP AND TRUNK

The hip joint is one of the most versatile joints in the body and is governed by some of the most powerful muscles of the body. Because of the ball and socket construction, skeletal configuration and possible load paths, the stabilization of the hip joints during various phases of movement involves many muscle groups. When weight is supported equally on both legs, the center of mass lies near the geometrical center line of the body (longitudinal axis) between the supports and the hip joints are relatively stable in the lateral direction. During movements involving a decrease of pressure on one leg (unilateral weight bearing), body segments must be re-oriented to place the center of mass over the supporting leg, and the hip joint must be laterally stabilized by increased muscle involvement. These same general observations hold for load transfer under dynamic loading conditions when the effects of inertial forces are added to the effects of gravity (weight) and the corresponding reaction forces from the snow change the direction. For equilibrium, the resultant reaction force must still pass through the body center of mass and this will stress the musculature in properly reorienting the body segments to achieve this goal.

An important aspect of this stabilization action is that concentric contraction of the gluteus medius (a muscle attached to the crest of the ilium and to the head of the femur, Figure 7.4) tends to draw the crest of the ilium down toward the femur with resulting upward movement of the other side of the pelvic girdle i.e. a forward raising of the hip. This natural tendency should be taken into account when analyzing hip involvement in skiing maneuvers.

Movements of the lower limbs through the diagonal planes result from diagonal movements at the hip joint. Such diagonal movements are combinations of motion in the traditional planes but are stronger than movements in individual traditional planes since involved muscle group arrangements are more favorable for diagonal motion. The muscle group arrangements allow more involved muscles to be placed at their optimal length diagonally and hence greater muscular force is available.

At this point it is necessary to discuss the involvement of the trunk in lower body movements. Physical laws (specifically the third law of action and reaction) dictate that to initiate movement of any part of the body or limb, one must either stabilize some segment relative to the earth or set some segment of the body into motion first. This must be so in order that the involved muscles will have something to pull against to impart motion to the desired limb or segment. The specific muscles involved for the interaction of the trunk and lower limbs are the rhomboids (upper back, diagonal from base of the neck downward to shoulder blade area), the erector spinae (Figure 7.5), the rectus abdominis (RA), the external obliques and internal obliques (abdomen, Figure 7.5). Note that these muscle groups join the pelvis to the upper trunk and are ideally located to impart diagonal plane movements of the two segments. If the lower body is stabilized, action of these muscles will impart motion to the upper body, if the situation is reversed, then motion of the lower body - specifically the pelvis and hips - will result. Thus motion can be transferred from the more massive trunk segment to the lower limbs via the pelvic girdle. Whether or not these muscles are significantly active in skiing will depend on the mechanics used by the skier in the execution of turns. Modern competitive slalom and giant slalom techniques do not seem to involve high levels of activity of these muscle groups beyond what one might expect from the requirements to maintain an upright stance (Hintermeister, et. al. 13), possibly as a result of more efficient use of skis and more refined muscle use in turn mechanics.

7.2 ELEMENTS OF PHYSIOLOGY

Physiology deals with the processes, activities and phenomena of living organisms. Of these processes, we are primarily concerned with the physiology of exercise. From the definition it is obvious that a detailed treatment of any one aspect of the physiology of exercise is far beyond the scope of this discussion. However, certain key elements should be understood by the instructor - and more importantly, by the coach. The elements I shall briefly review are related to the cardiovascular and respiratory functions, neuromuscular functions and sensory functions involved in the performance of skiing maneuvers. Before dealing with these specifics, two general concepts are noted: 1) physiological processes are primary concerned with maintaining homeostasis, or the stability of the internal bodily environment i.e.. temperature, chemical balance, bodily fluid equilibrium, pressure etc., and 2) in the human race, physiological variability is much less pronounced than anatomical (structural) variability. These facts will largely influence the guidance of skiing development through selection of proper training and conditioning exercises and help in understanding individual differences in performance.

7.2.1 THE CARDIOVASCULAR SYSTEM

The primary functions of the cardiovascular system are to provide bodily tissues with needed substances and to eliminate waste products resulting from chemical reactions. Knowledge of the detailed functioning of the heart, circulatory system and lungs is not necessary for effective instruction or coaching except in development of conditioning exercises for top competitive performance. However, the following key facts should be understood (I abbreviate cardiovascular system by the initials CVS):

Efficiency. Efficiency of the CVS contributes to endurance for sustained vigorous activity. Sustained vigorous activity, either aerobic or anaerobic, will result in fatigue. Alpine skiing is primarily an anaerobic activity, particularly competitive skiing. Fatigue is a complicated issue and depends on the nature of the activity, training, physiological status, and environmental conditions. Fatigue may result from the depletion of various metabolites, e.g. muscle/liver glycogen, blood glucose. Another contributor is the depletion of arterial and muscular oxygen. Accumulation of certain metabolites e.g. lactic acid may limit performance. During prolonged sub maximal activities fatigue is primarily due to the depletion of liver and muscle glycogen. At high altitude, where the partial pressure of oxygen is less, inadequate oxygen supply will contribute to fatigue. This is particularly true for individuals who are not accustomed to high altitude.

Endurance. To increase endurance of the CVS, overload must be applied. Overload can be applied by increasing intensity, duration and/or frequency of exercise. If the goal is to enhance anaerobic metabolism, then higher intensity training is the preferred mode. Generally increased intensity will result in more rapid fatigue of the performer.

Rate of breathing. The rate and depth of breathing are influenced by muscular activity, emotions, carbon dioxide concentration, oxygen deficiency and heart rate. All these are interrelated.

Hyperventilation. Hyperventilation (voluntary overfilling of lungs by successive deep inhalation) is often used to performance. Hyperventilation enhances performance by increasing arterial oxygen saturation. However, the amount of oxygen transferred to the blood stream is not usually limited by the amount of air in the lungs (except at extreme altitude where oxygen content of air is lowered) but by the oxygen saturation level of the blood. Hyperventilation also acts to "blow off" carbon dioxide. Carbon dioxide builds up in response to lactic acid build up in the blood as a result of anaerobic metabolism. The act of hyperventilation rids the body of carbon dioxide reducing its acidity and delaying the onset of lactic acid induced fatigue, thereby aiding performance.

Equilibrium. It takes time for all individuals to attain CVS equilibrium upon change of altitude. Adaptability (acclimatization) varies from individual to individual and may be dependent on the emotional state of the individual.

Speed. Top speed, rapidity of movement and reaction time are not dependent on the CVS.

Oxygen deficiency and carbon dioxide buildup in the bloodstream caused by holding the breath (untrained or inexperienced performers will often "forget to breathe") will hasten imbalance and hence fatigue. Vigorous exercise will cause the CVS to "fall behind" steady state, thus initial imbalance created by holding ones breath will hasten the fatigue process. Well-regulated breathing without conscious effort is a characteristic of well-trained performers.

7.2.2 NEUROMUSCULAR CONTROL OF MOVEMENTS

Since muscles respond generally as a result of nerve impulses, it is important to understand how the nervous system acts and to what degree conditioning and practice influence it. Nerve impulses travel in two directions: From the sensory mechanisms of the body which provide the senses of touch, taste, smell, sight, hearing and muscle/joint awareness (kinesthetic sense) to the brain and from the brain to the various functional mechanisms of the body. These impulses may be perceived on the conscious level or unconscious level. The nervous system is composed of infinitely large number of possible impulse pathways; these nerve impulse pathways are inherited and vary from individual to individual.

Coordinated and skillful movements are the result of complex neuromuscular processes resulting in properly sequenced and timed nerve impulses. Along with other physical capabilities, the nervous system matures with age and is not capable of the full range of operation until maturity. Thus the immature nervous system of small children will hamper speedy and precise impulse patterns and hence intricate movements. Since maturity is ill-defined and the rate at which it is achieved varies from child to child, it is extremely difficult to give guidelines as to when full capacity is to be expected. We do have gross manifestations resulting in the classification as "slow learners" and "fast learners". Many factors may influence "fast" and "slow" learning, so the distinction should arise in relation to motor skills only, all other factors being equal.

Several measures of time involved in neuromuscular control are important:

> **Reaction time**: The time interval between stimulus and beginning of response.
>
> **Reflex time**: The time interval between stimulus and beginning of automatic reflex response. Reflex time is the same as reaction time <u>only</u> for automatic or innate reflexes.
>
> **Movement time**: Time to accomplish the task. The reaction time for all voluntary movements directed by the brain is usually composed of reflex time plus thought or analysis time by the brain and is a measure of the lag in the functions of the nervous system. Reaction time can be improved somewhat through *specific* tasks. The majority of improvement occurs in thought or analysis time. As thought time decreases, the involvement of the conscious brain becomes less and less as the specific analysis patterns are relegated to lower levels of the brain. The final leveling-off time is achieved when a movement becomes a "conditioned reflex" and conscious thought is used only to amplify or diminish the learned reflex.

The most important innate (inborn) reflexes for movement analysis are:

> **Stretch reflex**: This is a reflex to maintain upright position of the body and to maintain body alignment. An example of this reflex is the head snap or jerk one experiences when falling asleep in a sitting position with the head unsupported. This reflex is also used by the body to increase force generation response e.g. use of counter movements.
>
> **Extensor reflex**: This is again a conditioned reflex activated by pressure on the bottom of the feet resulting in extension of all weight bearing joints. Its importance lies in maintaining balance and shock absorption when load is suddenly increased such as in jumping, for example. It is obvious that much of what we teach in skiing is intended to over-ride this reflex. We wish to flex our joints and extend them at will in response to variations in pressure. That this is difficult to learn is evident on any ski slope. Just look at all the skiers who initiate

a turn and then as the pressure builds in the turn, they react with a straight downhill leg.

Of primary concern to the instructor and coach is the nature and development of conditioned reflexes. A guiding principle is that skill is attained at the highest level when the reaction time approaches reflex time with diminishing conscious thought involvement - conditioned reflex. Thus the importance of developing kinesthetic sense from the very start is evident.

Key gross maneuvers, movements, and skills should be learned first and then more refined skills brought in. When the body encounters new situations, and they are in some sense similar to familiar situations for which a conditioned reflex has been established, it will react according to the conditioned reflex in combination with the appropriate innate reflex. Overriding by conscious brain involvement will depend upon the performers thought or analysis time in relation to the time available in the new situation. To train the analysis process properly for a maneuver which is to be of general utility in a given aspect of skiing, the maneuver should be practiced under all anticipated conditions. For example, skiing all types of terrain and snow conditions for the recreational skier and running as many different slalom courses and combinations as possible for the racer. Many runs over the same course or same type of course are detrimental to performance under a wide range of conditions one may encounter in racing. To decrease analysis time, a keen kinesthetic sense must be developed, primarily with respect to snow, terrain and speed variations. One means of improving a specific sensing capability is to isolate it from input from the other senses. For example, restricting the information received from sight and sound will cause development of keener kinesthetic sense. Isolation allows one to concentrate on the information from the desired sense.

The neuromuscular system is also involved in the manifestations of fatigue. Fatigue usually results in a loss of precision, power and speed. Muscular activity forms lactic acid (a by product) and the build up of lactate produces fatigue. Care must be exercised when practicing the final goal skill or maneuver under great fatigue so as not to encourage development of new, compensating neuro pathways which are detrimental to effective and efficient execution. Since the body must cope with the imposed demands, and it is incapable of doing so because of fatigue, it will call on other means to accomplish some of the task. However, if you anticipate skiing when fatigued, then development of such compensation is desirable.

Decreasing fatigue is usually achieved by better conditioning of the muscular and cardiorespiratory systems and by increasing the efficiency of movements. Efficiency of movement dictates blocking nerve impulses to muscles in opposition to a given movement (antagonists) and sequencing timing so that each force is applied at the time of maximum acceleration due to the previous force for maximum utilization of mechanical momentum. Maximum use of ballistic movements will improve efficiency. Most expert skiers are familiar with this concept as demonstrated by their ability to briefly relax between turns.

7.3 THE BALANCE MECHANISMS AND BODY EQUILIBRIUM

Successful skiing at all levels requires that the body be in stable equilibrium. (Equilibrium will exist if the resultant of all external forces passes through the body center of mass cf.chapter 4). The process of maintaining equilibrium when the body is moving involves the input from the sensing mechanisms and appropriate muscular adjustments. The sensing mechanisms are:

The semicircular canals of the inner ear: These fluid-filled canals are arranged in three perpendicular planes and sense rotation about any axis.

The otoliths (ear stones) of the utricle (located in the vestibule): These calcium deposits on fine hairs act as accelerometers and measure changes in linear acceleration

Visual: Direct and peripheral vision provide important clues to the body orientation.

Kinesthetic sense: The proprioceptors of the nervous system provide information about the relative positions and movements of various body parts. Information about acceleration, speed and orientation is also obtained from sensing pressure changes on the skin (face, bottom of the feet, etc.)

These sensing mechanisms can be confused by various means. First, all of them have sensing thresholds. Slow rotations, gradual accelerations and slow, smooth movements will not be sensed without visual input. In addition, shock loads and vibration will confuse the input signals to the brain hence the importance of minimizing head movements in all maneuvers. Fatigue will dull the senses since the nerve impulses will be impeded. This fact becomes critical when performing complicated, intricate movements at high speeds. The joint movements utilized to shift the body parts relative to the center of mass in response to perceived disturbances provide invaluable information about equilibrium via the kinesthetic sense. Immobilizing a joint will decrease sensitivity. Such decrease of sensitivity occurs with neck braces and high, stiff boots, for example.

High, stiff boots work in two ways to decrease the amount of kinesthetic information from the lower extremities: 1) They decrease ankle mobility thereby placing a greater burden on the muscles of the lower back, abdomen and upper legs, and 2) they decrease the feel of the bottoms of the feet for changes in pressure distribution and shock loads. Involvement of large muscle groups in maintaining balance decreases and complicates the initiation of small corrective adjustments involving minor muscle groups. Superposition of fine movements on gross movements requires very intricate nerve impulse patterns because of possible conflicting nerve pathway requirements. Of course, we benefit from the mechanical advantage that stiff boots provide us for transferring forces to the skis. The issue is one of compromise - the stronger, better trained skiers can benefit from the boot structure while not suffering the drawbacks I have indicated. Conversely, beginning skiers who are unable to produce any flexion at the ankle will not benefit from the mechanical advantage, but will suffer the drawbacks. With modern ski designs, the requirement to strongly pressure the front of the skis is less important.

Some final comments : There is much to learn about the function of the human body. This chapter introduces the key ideas and focuses on those aspects that are of most significance to skiing. For those who wish to pursue their study of the human system, I would recommend the Benjamin/Cummings Publishing Company series in Human Anatomy and Physiology. These are profusely illustrated and written at a level easily understood by the non-physician. Some are in self study form (e.g. "Anatomy & Physiology Coloring Workbook" 4th ed. by Elaine N. Marieb, PhD, 1994, others are references.

8. APPLICATION OF BIOMECHANICS PRINCIPLES TO SKIING: ALIGNMENT

Controlling the motion of the body is accomplished by manipulating the legs, feet and skis relative to the rest of the body. By controlling how the skis act on the snow, and thus how the ski/snow interaction forces act, we guide the body along desired paths and remain upright while doing so. Both guidance (motion of the body center of mass) and the problem of balance (motion about the body center of mass) depend directly on how the forces acting on the skis are transmitted along the body. Since the body is a collection of non-rigid links connected by joints of different properties, the efficiency and effectiveness of our motions is directly determined by body alignment.

8.1 ALIGNMENT

Alignment is the term used to describe the relative positions of the different body segments with respect to the load paths in the body. In the case of skiing, our primary concern is with the alignment of the lower body and limbs. The movement options (or movement capabilities) for skiing are primarily determined by the function of the following joints:

* The three joints of the foot and ankle (see Figure 7.1)

  i. talocrural joint in the ankle
  ii. subtalar joint in the foot
  iii. transtalar (midtarsal) joint in the foot

* The hip joint (head of the femur at the socket in the pelvis)

* The knee joint

* The spine

The knee joint (as noted in section 7.1.1) has limited capability for rotation, functioning primarily in flexion/extension. As such, it has a relatively minor contribution to alignment directly. However, the direction of knee flexion can contribute to tracking disorders. That is, depending where the knee moves upon flexion in relation to where the body center of mass is and where the skis are will influence the action of the ski edges on the snow. Also, the knee is the point of reference for most measuring procedures used to diagnose alignment problems. Motion involving the spine and thus the torso usually results from alignment adaptation. Given the existing alignment of the body, skiers will adopt compensating postures to cope with the loads encountered in skiing.

Correct alignment allows efficient use of the body. Recall that efficiency and effectiveness of movements, both in action directing movements and in reaction, reacting to upsetting forces, are the trademarks of the expert skier. The majority of external forces act on our skis. For balance, the resultant of the ski/snow interaction forces must act though the body center of mass. Since the connection path from the skis to the body center of mass is made up of individual bones, joints and connective tissues, these all must be oriented correctly with respect to each other. Essentially, we are concerned with how the body parts are oriented with respect to the line from the center of mass to the edge of the ski. If we are using both edges, the line will fall somewhere between the two, depending on how much force is applied to each ski. Remaining in balance while skiing then involves small adjustments of the body relative to this line. These adjustments in turn determine how our skis interact with the snow and thus determine our skiing success.

The manner in which individuals move to accomplish specific skiing movements will be determined by not only the characteristics of the body but by the interaction with the boots as well. Early efforts to cope with improper alignment involved the use of "canting" to adjust the relationship of the boots with respect to the lower surface of the ski(s). Cants are wedge shaped pieces of material used to selectively raise one side of the boot with respect to the ski surface. This technique of adjusting alignment is still useful today, despite its limitations. Alignment and equipment will influence the rotary and edging movements a given individual uses to control the skis. Depending on how you are aligned, your body will have a tendency to display certain observable movements under different skiing conditions.

What are the consequences of improper alignment? What movement compromises must we make? The compromises we make are in stance, movement initiation, rotary and edging movements, coping with the forces generated in turns, the quickness of our movements, ability to create angulation, and balancing movements. Movements that do not directly contribute to what we want to do in a given situation are wasted. If we cannot efficiently use our body to transmit loads, we risk injury. The skier's compensatory movements and stance can contribute to knee and lower back problems.

What causes our bodies to be out of alignment? For most people, it is the result of their natural skeletal structure. For example, the angle at which the head of the femur inserts into the pelvis can result in deviations in how the femur will transmit loads, as can curves in the tibia or anomalies in the foot structure.

The most common limitations to skier development encountered because of improper alignment are:

* The skier's potential to improve is limited because of difficulties in balancing and inability to fully make use of the ski design characteristics.

* The skier develops inefficient or ineffective movements to initiate, control and finish turns and maintain balance. These "bad habits" become so entrenched that they are never eliminated through practice or instruction.

* The skier is unable to ski smoothly or consistently when trying to link turns.

* The skier is unable to ski well on certain snow conditions. For example, the skis will not hold an edge on ice or will catch on "grippy" snow.

We would all love to put on our ski boots and find that we can ski with efficiency, resulting in effective use of the edges and turning movements. Unfortunately, humans have evolved developing skeletal structures and musculature which doesn't take the requirements for effective skiing into account. Factors such as curvature in the bones of your legs and how the primary load bearing bones mesh in the joints will influence how you are able to make ski turns. The amount of flexibility looseness of the joints will contribute to the compensatory movements that you may have to make offset alignment problems.

Fine tuning of body alignment is difficult and can be considered the inexact part of the alignment process. However, standard alignment measurement parameters have been established and for many individuals, significant improvements can be obtained through relatively simple adjustments. We know that your alignment is controlled by the way that your body interfaces with your ski boots and skis. Higher, stiffer boots have made proper alignment essential. Boots may contribute positively or negatively to the alignment equation. Recognition of potential alignment problems early on should help in the proper selection of ski boots. By taking advantage of the different design and function options available in ski boots, one can reduce the amount of alignment correction needed in most individuals.

8.2 CATEGORIES OF ALIGNMENT

There are three basic categories of alignment. These categories are described in terms of the relative orientation of the base of the ski to the line from the edge to the center of mass.

The three categories are:

1) Balanced, properly aligned and symmetric (both legs are the same). See Figure 8.1

2) Under-edged (edge-angle less than 90 degrees). See Figure 8.2

3) Over-edged (edge angle more than 90 degrees). See Figure 8.3

It is important to realize that a skier may be under-edged on one leg and over-edged on the other.

Proper alignment can be illustrated by drawing the reference line from the skier's center of mass through the point of contact of the ski edge with the snow. This line can be thought of as the "line of force transmission" since we know that the requirement for balance (body equilibrium) is that the resultant of all external forces must pass through the body center of mass. This is illustrated in Figure 8.1. If we are able to visualize an example of proper alignment, we will more readily recognize situations when it is compromised and why. Note that the extension of this line forms a 90 degree angle with the base of the ski. From experimentation and observations of skiers, we can establish that deviations from this position will substantially impair the functional use of our joints and muscles when skiing.

Balanced skiing creates all the sensations that we sense as enjoyable and exhilarating about the sport. To illustrate what happens in the case of the balanced, properly aligned skier, let's focus on carving turns. Carving turns in a parallel stance are arguably on of the goals of all recreational skiers. Proper alignment and mechanics make carving turns possible and easy.

Proper alignment allows us to turn or rotate the femur slightly in the (ball and socket) hip joint, which rolls the ski onto its edge. This ability of the femur to rotate medially (inward) also creates the complementary turning of the ski. The way our bodies are supported by ski boots and the way the boots are attached to the skis makes every femur rotary movement an edging and turning movement. Similarly, every edging movement we make with our feet either to increase or decrease the edge angle, will result in a movement of the femur, either inward or outward. You can test these observations yourself by sitting in a chair with the foot off the ground and experimenting with different combinations of movements. Move the foot to "increase or decrease the edge" and observe what your knee and femur are doing. This connection points out that turning

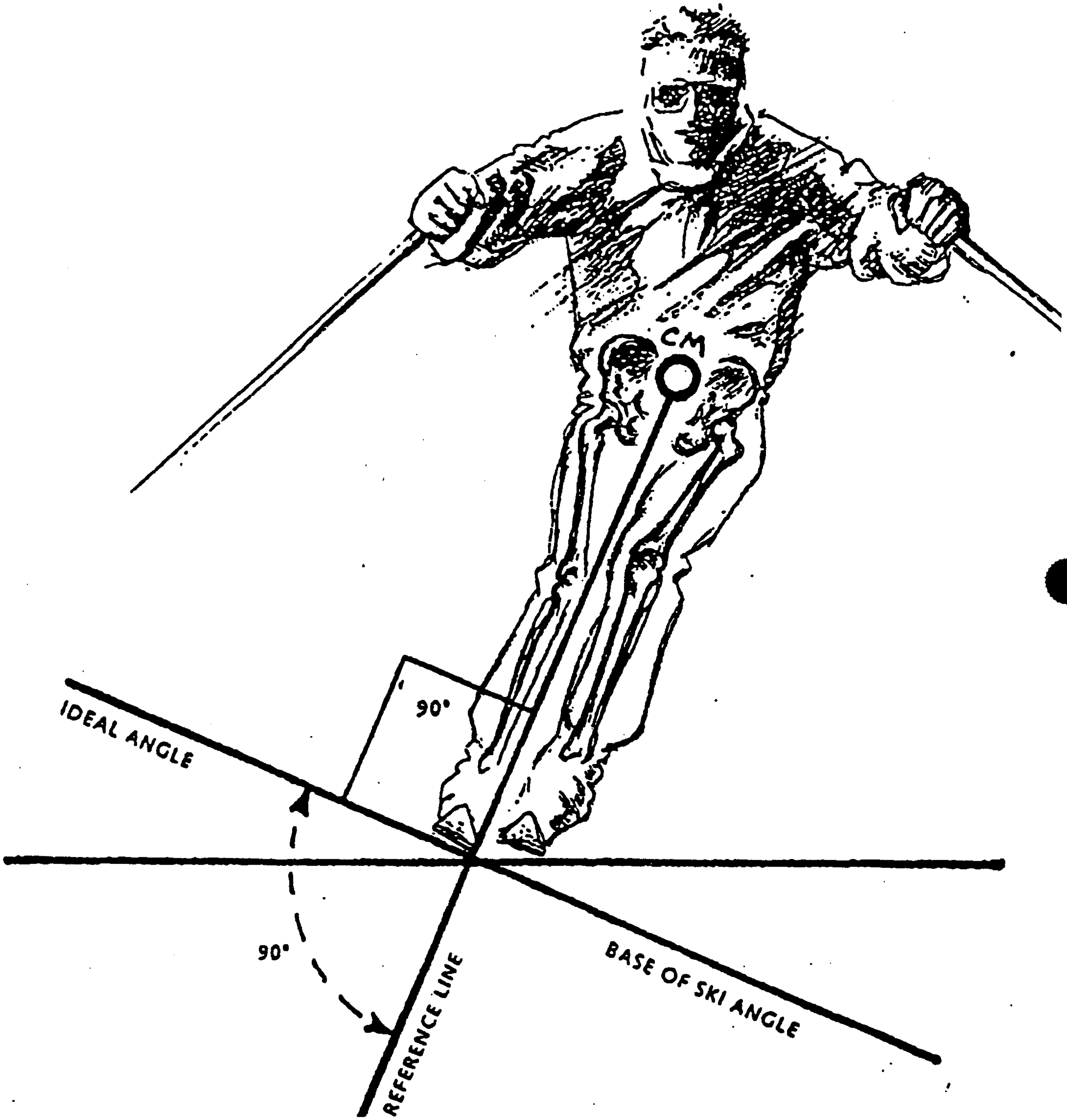


FIGURE 8.1 CORRECT, BALANCED ALIGNMENT

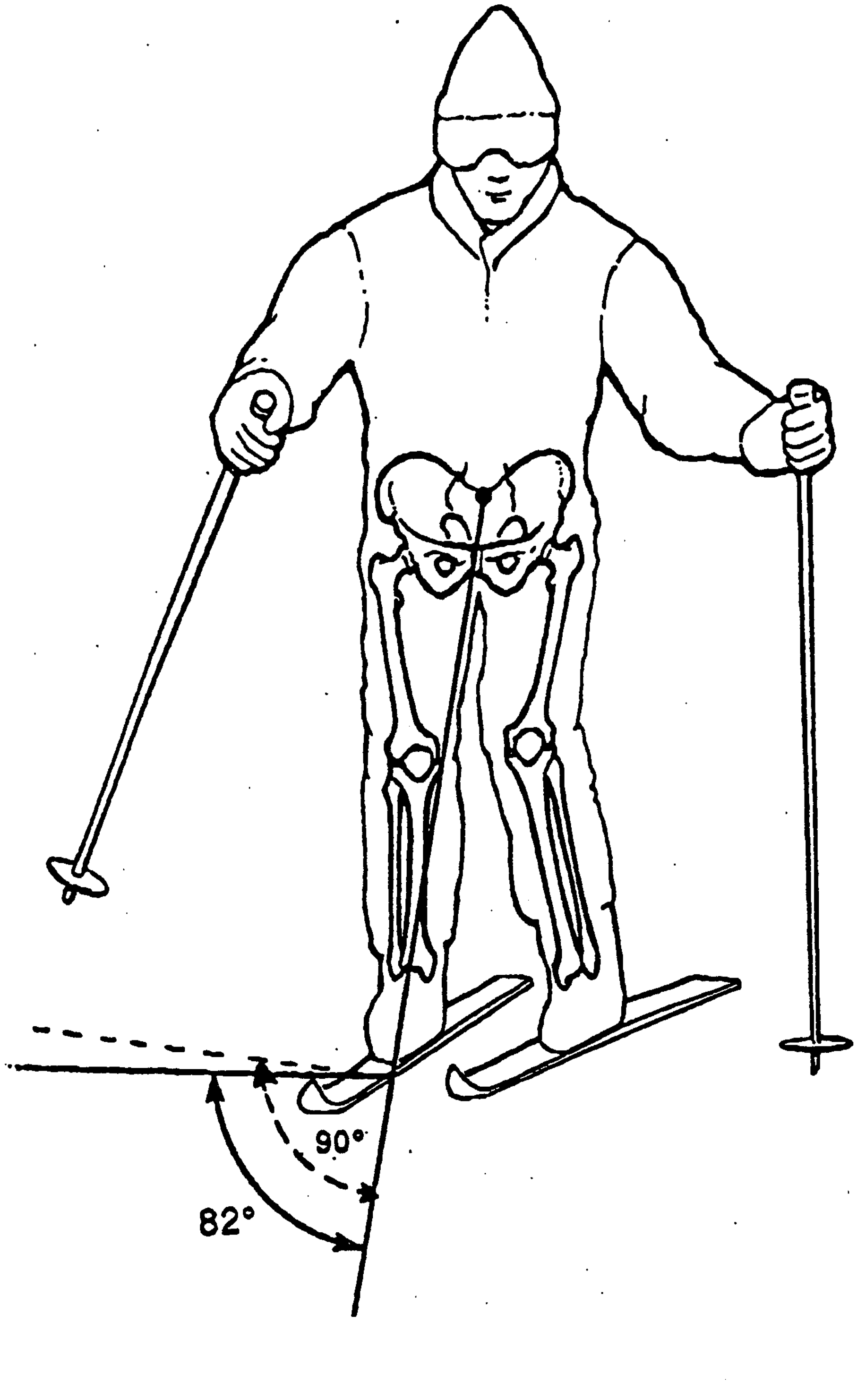


FIGURE 8.2 UNDER EDGED MISALIGNMENT

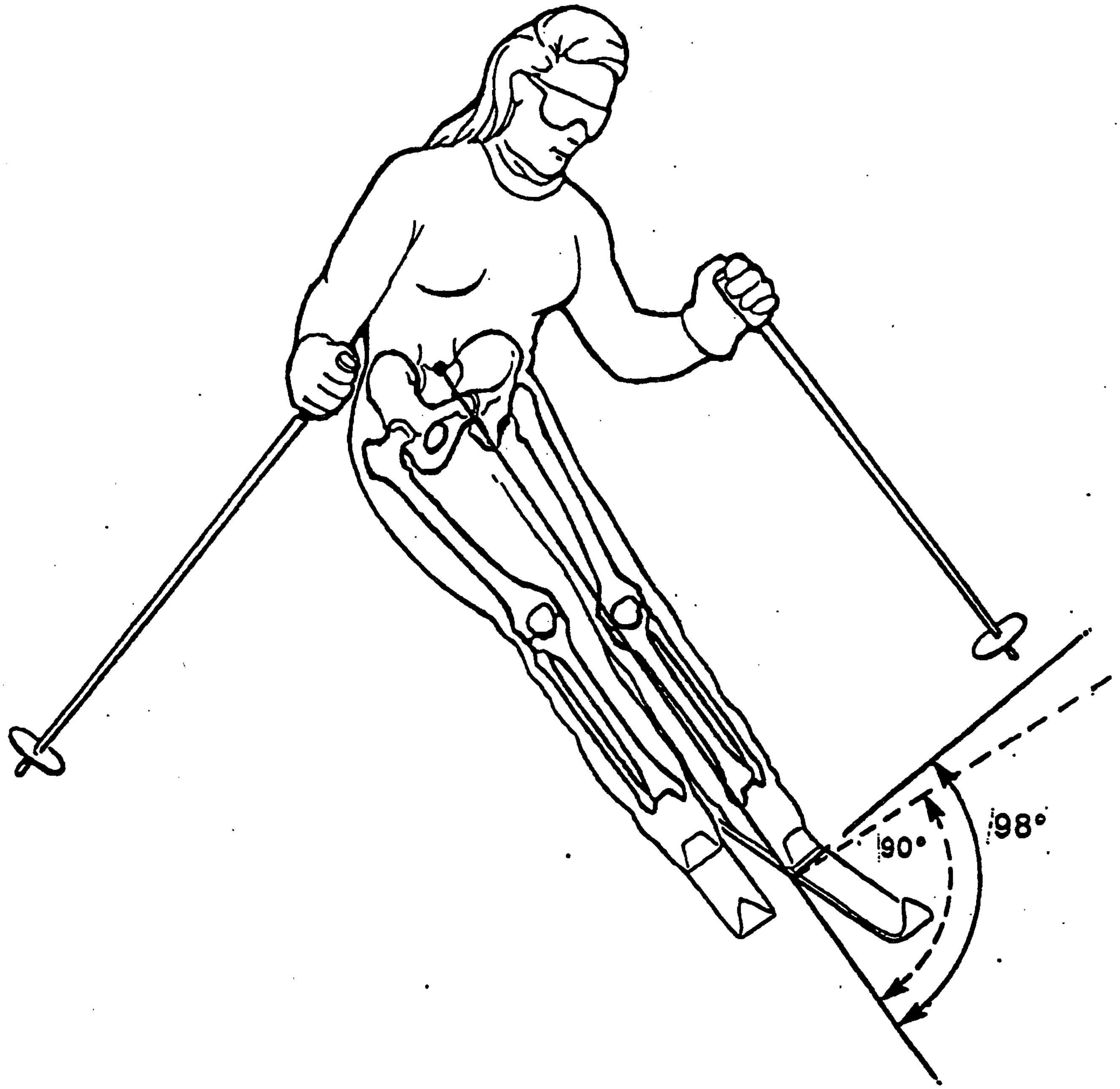


FIGURE 8.3 OVER EDGED MISALIGNMENT

and balancing are governed by subtle foot and ankle movements that allow the rest of the body to assume a functional orientation with respect to the turning ski. By playing around with different edging and turning movements while skiing, we can also readily establish the importance of establishing a fore-aft balanced stance. The conclusion of these experiments should convince you that small adjustments in fore-aft stance as well as small adjustments in alignment as defined here will create substantial changes in how the ski works on the snow.

The actions described above allow us to take advantage of modern ski design in making turns with carving. These actions put the ski on edge with minimum effort so that we can use the side cut and pressure the edge in turn initiation without pivoting action. The rotary forces generated by the femur turning and the amount of edge angle that results are critical elements to the continuation and control of the turn. When these elements are properly coordinated, we are able to guide the ski through a turn with precision and efficiency. Our joints arrange themselves so that we can effectively maintain a balanced stance against the strong reaction forces from the snow that are characteristic of a carved turn. At the point in the turn when the forces start to increase, the knee should not be the source of angulation or other body adjustment. Alignment of the body should allow the hip to be the major determinant in force transmission and maintenance of balance. To keep the ski deflected and turning, it must be pressured. Once the ski loses reverse camber, carving will be lost. The radius of the turn is adjusted with minor subtle body movements.

It is important to understand how alignment angles larger and smaller than 90 degrees to the line of force manifest themselves in skiing. Angles less than 90 degrees will create a "flatter" relationship of the base of the ski with respect to the snow surface. This is the situation for the under-edged skier who feels no grip or edging capability in a turn. The tail of the ski keeps skidding as the turn progresses. More efforts to gain edge and grip increase the skidding. To stop the skidding, the skier moves the body opposite to the direction of the turn. A strong countered position (body rotated in the direction opposite the direction of the intended turn) at the beginning of the turn is often an indication of compensation for under-edged alignment. Ice or very slick hard snow amplify the problems for the under-edged skier.

In the case of the over-edged skier, angles more than 90 degrees bring the ski to an edge too quickly. This often results in larger edge forces than the skier can manage. The sudden large edge forces are most often seen on "grippy" snow surfaces that result from packing of new, wet snow. The problems of the over-edged skier are amplified under these conditions. The skier tries to manage this situation by decreasing the pressure on the ski as well as the edge angle. Both these actions cause the ski to have less reverse camber and the design features built into the ski to aid turning are not used. The skier compensates by generating turning forces from rotary movements higher up in the body, e.g., from the hips, shoulders or arms.

8.3 THE MECHANICS OF ALIGNMENT

Recall from the discussion of the basic concepts of mechanics that the sequence of events for a ski turn requires that we first do something with our bodies to manipulate the skis in such a way that the snow can exert turning forces on them. Once such forces are brought about, we start to turn. From this observation it is clear that the most efficient way to control the skis is for the required movements to originate as close to the skis as possible. Thus, the movements that initiate turning, edging, steering and guidance should originate inside the ski boot with the foot and ankle. If the actions of the foot and ankle are detrimental to efficient transmission of movements to the boot and hence the ski, properly designed foot beds (or orthotics in severe cases) can help correct the difficulties. There are situations where the muscular actions that initiate changes in the path of the body center of mass will start elsewhere. For example, earlier I gave the example of initiating cross-over by relaxation of the quads and abdominal muscles, thus allowing the center of mass to travel in a straight line rather than follow the existing turn. Note however that this relaxation by itself will only change the edge(s) but not impart any rotary movement. To supplement this action, we once again use the movements originating in the foot and ankle.

When the turn develops and forces start to build, the skier should feel pressure along the sole of the foot. The smaller the force needed to start the turn, the better the skiers position and balance. Great skiers have such perfect position that they show very little movement to begin turns, just flow beautifully from turn to turn. The secret is in the feet and ankles. Foot movements that involve the ankle start the turn: Simply everting the foot (turn the sole of the foot to the outside of the turn) pushes the ankle against the inside wall of the boot, the engaging edge starts the turn. Increasing ankle pressure to the side wall of the boot produces more edging. Lateral balance then is maintained by increasing or decreasing the pressure against the boot. As the turn develops, the body moves to the inside of the turn. This movement brings the body into an inclined position thus allowing the skeleton to carry the forces.

Of course, we do not control these actions with conscious thought processes. We don't think: "How much femur rotation do I need?" Am I edging enough?" "Is this the proper time to increase inclination?" As you shall see in the next section, human motion control doesn't operate that way. If we had to "think our way through a turn" we could never ski at any appreciable speed.

So what should we look for in the under-edged skier? The under-edged skier will be overly flexed and (usually) levered forward in the boots. One diagnostic is to look at the skier in a basic traverse on a hard slope. The under-edged skier will be unable to show both skis equally edged to the snow. There is a major difference between the mechanical description of an under-edged skier and what this skier looks like to people when observed on the snow. On the snow, this skier from the boots up demonstrates a tremendous edging potential. That is, he or she visually presents considerable "knee angulation" or a "knock kneed ", "A frame" stance. (Remember that "knee angulation" is really a misnomer and what is observed originates in the hip joint). This posture actually reduces edging ability, contrary to appearances.

Why do some individuals have this skeletal alignment? Anatomically the under-edged skier's feet, ankles, and legs determine a position that brings the knees together (often touching) but leaves the feet up to six inches apart, showing a pronated stance. When standing in ski boots on a flat surface the knees are touching but the ski boots are apart and flat on the surface. The contributing anatomical factors are pronation, tibial torsion and tibial curvature.

So what happens when this skier turns? When the under-edged skier initiates a medium radius carved turn from a straight run, the dominantly pressured ski is rolled to an edge and the tail starts to skid. The amount of rotary force and edging are out of proportion. the femur of the under-edged skier is already rotated inward (adducted or rotated medially) as we have observed from the straight run.

Remember that the knee is limited in lateral motion ("knee angulation"). But with the leg flexed and the femur rotated, the body appears to achieve angulation with the knee. Here

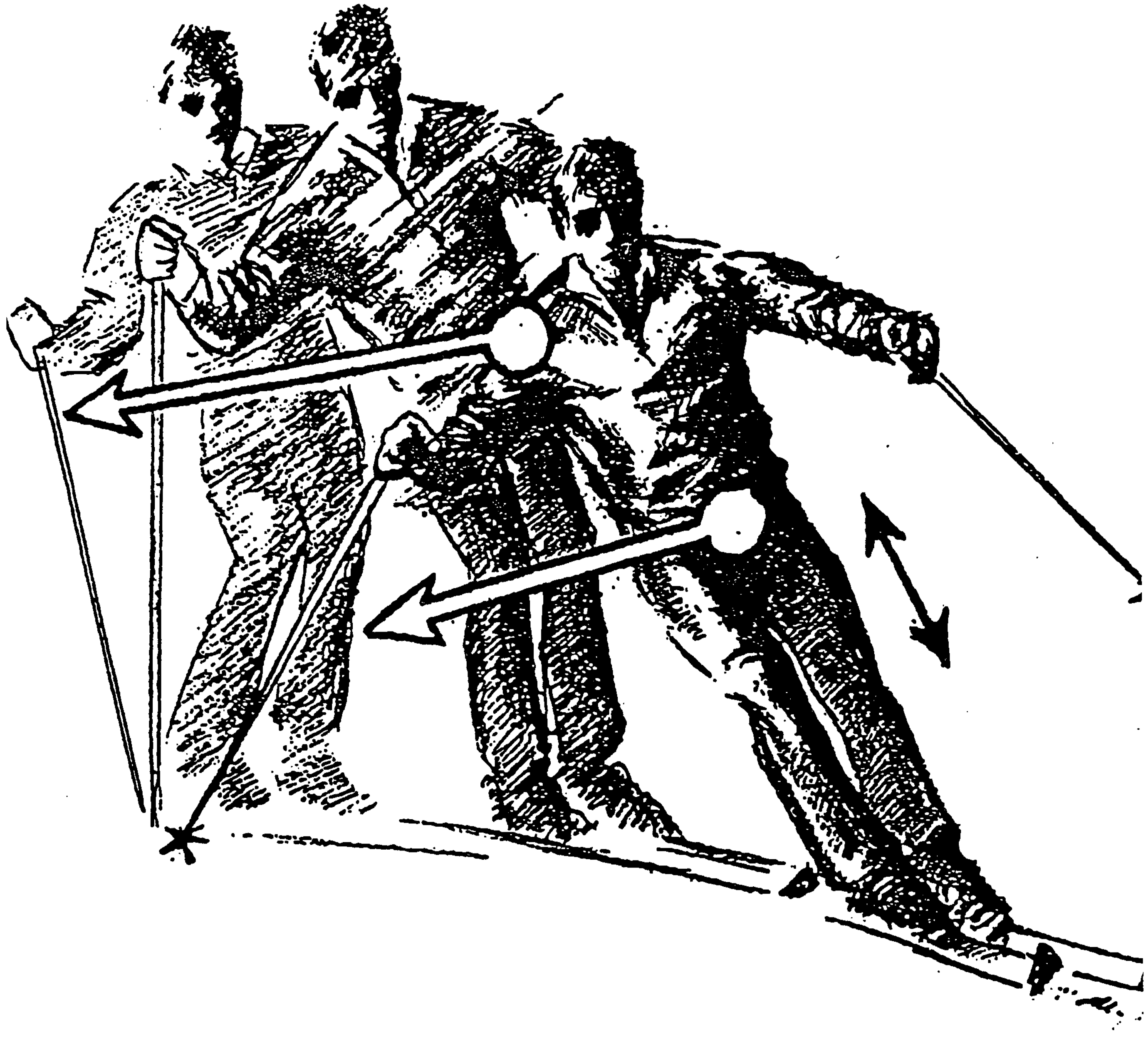


FIGURE 8.4 COMPENSATION OF AN OVER EDGED SKIER:UPPER BODY INITIATION

is the root of the problem. When the skier tries to initiate a turn by rolling the ski onto the edge, the femur already has some degree of rotation due to the basic stance. Rolling the ski further contributes to an already weak position. The resulting rotary force is too great for the angle of the ski edge to the snow and the ski starts to skid. Put another way, the ski edge angle to the snow is insufficient to sustain the forces. Use of the hip to increase angulation is difficult since lateral balance is already precarious with the ski skidding from the outset. Thus the hip is forced into rotation with the turn because the body has not found enough edge and resisting pressure to attain good balance.

For a ski to be used as designed, it needs enough edge pressure to sustain the turn. The excessive knee angulation we see in under-edged skiers diminishes the ability to pressure the edge as required for engaging the ski in a carving arc. When the ski skids from the beginning of the turn, ski design is not properly used, reducing skiing performance.

Experienced skiers who are under-edged will have developed compensatory movements. A skier with a strong athletic sense and movement awareness will compensate for under-edging by decreasing the rotary torque by reducing femur rotation. The movement involved requires countering the hip early in the turn. When the hip is countered, the downhill leg can be straightened. This action also decreases rotary forces and helps achieve edge angle though body inclination rather than knee angulation. However, as a result the fine tuning motor control capabilities of the foot and ankle are restricted. The ability to vary the turn shape as well as react quickly is greatly diminished.

On the other hand, the over-edged skier has just as much difficulty as the under-edged skier in making the ski work properly as designed. The skis feel very reactive, grabby and railed (a condition when the ski edges are not flush with the base and protrude as rails). Many skiers who are over-edged have learned that extreme beveling of the edges improves performance. Beveling will help reduce the severity of the symptoms, but cannot cure the problem.

So what do we see when we look at the over-edged skier in a turn? From the front view of the skier in a straight run the skier demonstrates knees that have some space between them, yet the skis are close together. The stance is very upright, with minimal flexion. From a straight run, the dominant ski is pressured and rolled to an edge. The femur has moved from outside of vertical to a vertical alignment over the ski. The tendency of the ski is to catch the edge quickly and continue down the fall line. The ski has difficulty starting the turn because it has little help from the femur in providing steering action. For this skier we see that edging is too strong and the rotary forces too weak. In this over-edged alignment situation, adequate femur rotation has not been achieved. The adductors do not have the strength to overcome the edged ski. Flexion and medial adduction could not occur therefore the knee could not move under the body and to the inside of the turn.

Edging has been accomplished but the rotary forces are not adequate to start the ski into an arc. Remember that we are looking at a medium radius turn for which the radius is significantly smaller than the natural turning radius of the ski. Thus rotary forces to steer the ski must be supplied. The skier then has the following options:

1) Lean the upper body toward the mountain to get the ski up on edge more gradually and allow the sidecut of the ski to contribute more to the turning action.

2) Apply gross rotary forces by turning the upper body, either in the direction of the turn or counter to it.

Figure 8.4 illustrates an example of compensation by an over edged skier: use of the the upper body for turn initiation. The force generated by turning the upper body will help release the edge and start a skidded turn. Leaning the upper body will place the skier in a precarious balance situation. Neither compensation approach is an effective and efficient way to ski.

The experienced over-edged skier does use these techniques to compensate and develops quite sophisticated ways to do so. For example, the skier may use leaning towards the mountain at turn initiation. As the ski starts to react to increased pressure on the edge, the skier will gradually bring the upper body to a more square to the skis posture as the turn progresses. This action will create a seemingly controlled steering and guiding ability. The inside arm will drop and get behind the body when completing the turn. This method is very subtle a works to control pressure as well as help in turning. This skier will have extreme difficulty in making short radius turns and controlling pressure. On harder snow chattering skis and wiggly knees often result of too much edge. The ski actually slices the snow too sharply without enough pressure on it to hold in the snow.

For subtle and refined turn initiation and control, the skier needs to be able to use the lower body effectively and efficiently. To do so, the boots and bindings must be adjusted to create proper lower body alignment.

9. THE HUMAN AS A CONTROL SYSTEM

I have stressed in all the discussions of the mechanics and biomechanics of human motion that we should consider the activity from the point of view of *control.* This viewpoint assumes that a movement task has been determined, some objectives have been selected for the execution of the task and then one proceeds to execute the task. These concepts are fairly general. Note that we can think of the task in very specific terms, such as "demonstrate this particular parallel turn", and that the objectives can be specific as well, such as "make the turn with carving." Or, we can think of a whole set of tasks in general terms: Run the race in minimum time, ski the moguls with grace and control, etc. Once we have decided what the task is and how we are to judge whether or not we are successful, then successful execution will require movements that support the task while countering the disturbances that tend to disrupt the successful execution.

This is the same problem that automatic control systems must solve. For example, when control systems engineers design automatic landing systems for aircraft, the task is specified as " control the aircraft to follow the desired glide path at the desired speed and touch down on the runway at a given point with given velocity" and the system "must do this with a defined allowable error while subjected to air turbulence disturbances." The automatic control system is composed of suitable sensors (altimeters, air speed indicators, attitude sensors, radar etc.) suitable actuators (engines, elevators, rudders, ailerons, flaps, etc.) and the control actions to be taken are defined by the control computers which process the sensor information and send the appropriate signals to the motors that move the actuators or to the engine control systems. The fundamental approaches to automatic control are to use *feedback control laws* (the rules for the control computer) or the use of *open-loop control laws*.

In the engineering sense, feedback control (closed-loop control) is the use of information that the sensors provide about the current state of the system. For my aircraft example, this might be the current altitude, heading, forward speed, rate of descent, or attitude. This information is compared to the desired state, errors are formed, and based on these errors, signals are sent to the actuators that then move to elicit corrective reactions from the environment. The key issue about feedback control is that the results of control action are always delayed, since the system continues to move while the information is measured, the errors are determined, the corrective action computed, the actuators are able to move the control surfaces and finally, the control surfaces are able to elicit the response from the environment to change the state of the aircraft. Simply put, inherent in any feedback control system are time delays.

The alternative approach is to use open loop control. This approach assumes that one has good information about how the system will move given some inputs and that disturbances can be neglected. Then, based on the defined control objectives, the appropriate control actions are determined, stored in the computer and executed concurrently with no regard for the information that the sensors are providing about the actual state of the system. This approach has the advantage of minimizing time delays. The problem of course is that the pre-computed control laws depend upon the assumed state of the system at all times. So if the actual state is not what the designer assumed, or there are disturbances that cause the actual state to be different from what it is assumed to be, then open-loop control can cause disastrous results.

Automatic control systems engineers usually consider all aspects of the problem and devise systems that minimize time delays, maximize performance while making the systems insensitive to expected disturbances and incomplete knowledge of the systems that they are working with. Automatic control systems are an integral part of modern technology. From household appliances to transportation systems to entertainment to medical care - the list goes on and on. Everything goes better with control.

So why is an understanding of the basic concepts and limitations of control significant to the understanding of human motion and the learning of motor skills? Because motor performance is a control task and understanding what is involved in controlled movements and the inherent limitations will serve to guide learning experiences. Research in motor control and learning helps guide the development of teaching and coaching methods as well as helping to understand how the learning process must evolve. The text by Schmidt (1988) serves as an excellent entry point into the field, with extensive references to specific research literature. Some of Schmidt's text is quite technical, however, the basic concepts are presented in a way that is accessible to the non specialist reader. I cannot address all the relevant issues here (after all, Schmidt's text is over 500 pages with 39 pages of references!). Even so, I can point out some general guidelines that one should keep in mind in sports instruction.

First, human motor control does not neatly fit into either a closed-loop control framework or an open-loop framework. As I noted above, closed loop (feedback) control is inherently limited by time delays. This means that there are limits to the speed with which movements can be performed if the human operated strictly in a feedback mode that includes information processing at the cognitive level. The conventional interpretation of a feedback control model as applied to human motion control assumes that the brain is involved in some form or another, i.e., we do have an information processing computer in the control loop. An indication of the basic limits of such a system can be obtained if one considers the typical time delays involved in reacting to some stimulus or perceived disturbance.

At the most basic level, the minimum time to respond is the *reaction time* (or response time), one of the basic abilities that the person has. The response time thus varies from individual to individual (say in the range from 0.2 seconds to 0.4 seconds) and also is one of the characteristics that changes with age. One study of the effects of age on the reaction times reported a decrease in reaction time from 0.35 seconds from age 6 until about age 19 to 0.2 seconds with a subsequent increase to about 0.25 by age 60. What does this time delay mean in terms of skiing? Say you are moving at 30 miles per hour. In 0.35 seconds, you have traveled 15 feet; for 0.2 seconds, 8.8 feet. For 45 miles per hour, these distances increase to 23 feet and 13 feet respectively. So if you are reacting to disturbances from the snow, and depending on a feedback control mechanism to balance yourself, you are a long way down the mountain before you can even start to do something about it. The handicap of the very young and the old is also clear in this illustration. For further discussion of the effects of aging on the basic abilities, see Schmidt.

There is considerable evidence that humans control movements in very complicated ways, neither via simple feedback control loops including the brain in the loop nor open loop control mechanisms. Rather, the human control system is probably a hierarchical structure with multiple embedded feedback systems acting in concert with open loop control schemas. Some of these feedback loops operate without involvement of the brain, others do use the information processing capabilities of the brain to one degree or another. In general, what parts of the system are involved is probably determined by such factors as the sensors required (e.g. vision, proprioception), the nature of the movement (slow, fast, guided, unguided) goals of the task and so on. It is known that the movements involving conscious brain activity will have the longest characteristic times. If the events one is trying to control happen on a faster time scale than these characteristic times, then the task would be difficult indeed unless other control mechanisms are invoked.

We know that in skiing many things happen very rapidly, well under the time scale of characteristic reaction times. So even if we neglect other sources of time delay such as movement initiation time after the stimulus has been noted, we would not be able to ski if the brain were involved in all skiing movements. This is where training and practice come in: We may start with heavy brain involvement, but with practice, this involvement progressively decreases until we perform the task "reflexively". We are in effect establishing the required open loop control programs and/or local feedback controllers to cope with a variety of situations.

One interesting aspect of skiing is that many of the required movements are in contradiction to what the body knows already how to do reflexively. The most obvious example is the extensor reflex. This reflex causes an extension of the joints in response to a sudden increase of pressure on the soles of the feet. But in skiing, we often need to flex the joints rather than extend under increased pressure on the skis. So we see this conflict on the slopes in all beginners and intermediate level skiers - the legs go stiff when they should be flexing and vice versa.

Thinking about the human as a control system we recognize that training and experience determine such critical factors as timing, coordination, accuracy, efficiency and effectiveness of the overall movements. This knowledge should temper our expectations of our students as well of ourselves as athletes. We know that learning of new movements will initially require involvement of the conscious brain and that with practice this involvement will decrease. There are limits to the number of independent "bits" of information that the human mind can consciously process simultaneously. This is the basis for the generally accepted adage: "multiple instructions will only confuse the learner." Thus at all stages of learning a new task, when the brain is involved, simplify your instructions.

10. INDEX

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APPENDIX I. ABILITIES AND SKILLS

Fundamental to ATS mechanical movement progressions is the concept of motor skills as basic building blocks. In this appendix, I present some information clarifying the skills concept and the related concept of ability.

What is a skill? A quote from Singer (1975) illustrates some of the difficulty in achieving a succinct definition.

> "The term skill, like the term learning, is difficult to measure and interpret. It may have various connotations, depending on what is to be defined and who is defining it. Skill can refer to a particular art performed or to the manner in which it is executed. All physical education activities may be considered skills or as being comprised of skills, and the degree of proficiency reflects the skill level.
>
> Skill is a relative quality, not to be defined in absolute terms. Performance displayed by an individual may be so outstanding as to warrant his being considered skilled, by comparison with a group of his peers on the neighborhood field. The same person, when placed with members of the varsity team may appear relatively unskilled. Skill, as demonstrated by performance, is an indication of what has been learned. Skill and performance can be greatly influenced by a host of factors that may have psychological or emotional origins. However, it is usually thought that the highly skilled individual will be able to perform consistently, regardless of the factors present that may cause the 'average' person's performance to fluctuate."

A good working definition is provided by E. Fleishman (1969). "The term SKILL refers to the level of proficiency on a specific task or limited group of tasks, e.g., it is task-oriented." From this we can see that "**skills** (are) movements that are dependent on practice and experience for their execution, as opposed to being genetically defined". (Schmidt, 1988)

The term 'ability' is thought to be a more basic characteristic or trait which may be used in the development of a skill. That is, abilities are genetically determined or develop as a consequence of the normal processes of growth and maturation. Thus a specific skill is acquired through practice and experience, with the skill level that is attained depending on a certain collection of abilities.

Abilities are thought to depend on both genetic and growth factors, and as such represent the traits or inherent factors that the individual brings with him or her when beginning to learn a new skill. According to Schmidt (1991) approximately 20 to 30 cognitive and motor abilities have been identified so far. Schmidt estimates that perhaps a total of 50 will eventually be identified. From the list identified thus far, the following abilities are important to sports such as skiing.

Control precision: the ability to execute fine, highly controlled (but not over controlled) muscular adjustments, primarily where large muscle groups are involved (arm-hand as well as leg movements). This ability is critical for tasks where such adjustments must be rapid and precise.

Multi-limb coordination: the ability to coordinate the movements of a number of limbs (and trunk) simultaneously.

Response orientation: the ability to select the correct movement in relation to the correct stimulus.
Reaction time: the speed with which an individual responds to a stimulus when it appears.
Rate control: the ability to make continuous adjustments to movement in speed and direction.
Postural discrimination: the ability to respond to changes in postural cues in the absence of vision in making precise bodily adjustments. This is a key to understanding why some people are better skiers in poor visibility conditions than others.
Kinesthetic sensitivity: the ability to discriminate small changes in movement i.e. sensory information from your own body about relative joint positions and movement, muscular tensions, and orientation in space.
Movement speed: the ability to move limbs rapidly after reception of a stimulus.

Note that all of these abilities may be improved somewhat with practice of selected tasks. (The basic reaction time appears to be the most constant and difficult to improve by practice). However, the basic abilities that an individual brings to a given motor activity are in a sense the inherent limitations of that individual to accomplish a high level of skill in that activity. Although the terms skill and ability are often used interchangeably in casual conversations, they are not synonymous and one should be careful to distinguish between the two concepts when discussing motor learning issues.

One other aspect of the abilities issue is that one can identify capabilities that characterize the physical and/or structural aspects of the body, and these are sometimes referred to as abilities. Fleishman identifies some of these as: Static flexibility, dynamic flexibility, static strength, dynamic strength, trunk strength, explosive strength, gross body coordination, gross body equilibrium, cardiovascular endurance. These define the underlying physical fitness and are trainable. Since they are not restricted to specific movements (as we do with skills) and are trainable to some extent, these lie somewhere between skills and abilities. There are other physical characteristics that limit human performance e.g. height for basketball players, weight for football linesmen, but these do not seem to play a major role in skiing.

Observe that balance is not included as a basic ability, rather, balancing (the action of maintaining a desired orientation of the body in space, what we think of as equilibrium) is a task-specific activity, thus a skill. To remain in balance, a person is constantly reacting to forces and moments that are trying to change the desired state. In this sense, one is never still but always moving. The deviation from equilibrium must be great enough to trigger a sensory message which, in turn, triggers the physical reaction. How far from equilibrium one must deviate before an awareness of imbalance is registered varies from person to person, and the response to imbalance is infinitely adjustable through conditioning of strength, agility, and experience. Various sensory mechanisms are responsible for monitoring one's position, e.g., the inner ear, eyesight, and proprioception in the muscles and tendons.

The last topic in the abilities/skills area I wish to mention is the notion of general motor ability : the concept of the "natural athlete". That is, a person who is a "natural athlete" - one who possessed a high level of general motor ability - could learn any motor task easily and perform well. This notion was popularized in the 1930's and seems to persist in the general public, as well as among athletes and instructors who have not studied motor control and learning literature. Recent findings indicate that the hypothesis of general motor ability is not valid (for more on the subject, see Schmidt, 1988, Chapter 10). The popular observation that there are individuals who seem to excel in many sports and acquire new skills easily seems to be in contradiction to these findings. The usual situation in these cases is that the individual in question is, or has been, active in many different sports and motor activities, has a very broad experience base and is usually quite adventurous in attempting new activities. As Schmidt observes, the "rich get richer". If you have a broad base to begin with, it's easier for you to increase it. If you are fearless, this increase is the most rapid (provided you survive the experience!).

Development of ATS involved an eventual isolation of three basic skills as being fundamental to learning how to ski. Prior to publication of ATS, these were identified as *edging*, *turning*, and *pressure control*, with *balance* viewed as an overlying ability. A convenient graphic, the Venn diagram, has been extensively used to present these concepts. This diagram depicts three interlocking circles within a large circle. The three interior circles represent the three basic skills and the enclosing circle represents balance. The usual interpretation has been that the overlapping area of the interior circles represents the integration of the three basic skills, and as the overall proficiency of the skier increases, the area of overlap increases. Specific actions of the skier are usually analyzed in terms of these skills, with all three being present to various degrees of intensity in all maneuvers, from the very basic introductory moves to the most advanced.

The skills concept has proven to be an effective and efficient way to view all movements of skiing. The current understanding of skills differs somewhat from earlier descriptions in that *all are now movement focused* and *the concept of control* is integrated in the skills definitions. Thus we understand the fundamental skills to be

- balancing movements
- rotary movements
- edge-control movements
- pressure-control movements

For a deeper understanding of motor skills and abilities concepts and how they relate to sports in general, you are encouraged to consult Schmidt (1988) and the references given there.

I would be remiss if I didn't comment on what is known about the effects of age on skilled performance. Not only do we teach students of all ages, we continue to age ourselves, and our self-expectations should be realistic in view of what biology is doing to us. Simply put, past the age of about 25 years, a progressive decline occurs in just about every measurable aspect of motor performance as determined by the fundamental abilities identified above. The most consistent finding is that people become slower, as measured by such things as reaction time and the related movement time. These findings should not be used to conclude that as one gets older, performance of sports skills must necessarily decline.

For most individuals, with the possible exception of those who have reached their inherent peak performance levels by the age 25, continued learning and improvement are possible well into their later years. That is so because for most, the limits set by their inherent abilities have never been reached. The most obvious examples of this can be seen in track and field, where performance is measured quantitatively and with the same "yardstick" for everyone. How fast did you run one hundred meters and how fast are you running the distance now? How far did you long-jump?

APPENDIX II MATHEMATICAL FORMULATION OF MECHANICS

In this appendix I will develop the necessary mathematical models for analyzing skiing mechanics. For those who are not interested in the mathematics or do not have the necessary background, nothing is lost by skipping this material. There are some, however, who like to work with the shorthand of mathematics. This appendix is to serve as a reference for them. Another reason for including an accurate mathematical formulation of the equations of motion is that there are people who enjoy simulation of dynamics on a computer. Given the existence of software that can easily generate numerical solutions to systems of ordinary differential equations, one can expect more of this type of experimentation. Of course, to do so, one needs to make assumptions about the forces involved. There are limits to the complexity of problems that can be solved without resorting to computers. As an example, in a later section of this appendix I present the formulas that define the terminal velocity that a skier can attain. To find numerical values, one still needs to know something about the friction between skis and snow and the air drag on the skier's body. These are not necessarily easy to determine. In fact, most problems that one can pose in mathematical form to describe motion cannot be solved without the aid of a computer.

A. 1 THE EQUATIONS OF MOTION

I will restate Newton's and Euler's laws here in modern mathematical notation. Recall that Euler's extension of Newton's laws to rigid bodies of finite dimension adds more equations to describe the dynamic state of the body. I assume that the effects of all other bodies that come in contact with the body of interest have been replaced by their contact forces, using the third law.

The general equations of motion of a rigid body free to move in space are governed by the two vector second order ordinary differential equations which describe the motion **of the center of mass** (CM) and the motion **about the center of mass**. These are:

Motion of the CM: $$\frac{\mathbf{d}(\mathbf{m}\vec{\mathbf{V}})}{\mathbf{dt}} = \Sigma\vec{\mathbf{F}}$$

or $$\frac{\mathbf{d}\vec{\mathbf{P}}}{\mathbf{dt}} = \Sigma\vec{\mathbf{F}}$$

where:

$\mathbf{m}$ is the total mass of the body

$\vec{\mathbf{V}}$ is the **inertial velocity** of the body center of mass

$\sum$ is the short hand symbol indicating the vector sum

$\Sigma\vec{\mathbf{F}}$ is the resultant of **all external physical forces** acting on the body (i.e. the result of summing all the forces)

$\frac{\mathbf{d}}{\mathbf{dt}}$ is the total time derivative or rate of change with respect to time

$\vec{\mathbf{P}} = \mathbf{m}\vec{\mathbf{V}}$ is the (linear) momentum of the body

Motion about the CM: $\frac{d\vec{\mathbf{H}}}{dt} = \sum \vec{\mathbf{M}}$

where: $\vec{\mathbf{H}}$ is the total angular momentum about the center of mass

$\sum \vec{\mathbf{M}}$ is the resultant moment (or torque) about the center of mass of the body. This resultant moment includes pure torques and couples as well as the moment contribution of the external forces. The moment of a force for use in this equation is defined with respect to the center of mass. The magnitude of the moment is equal to the product of the magnitude of the force times the perpendicular distance from the CM to the line of action of the force.

The total angular momentum of a rigid body is a product of its total angular velocity with respect to inertial space and its inertia properties, which in turn are defined by the shape of the body and the distribution of its mass (density). The exact mathematical form is somewhat involved to write out. It turns out that for the purposes of analyzing skiing, the exact form will not be needed.

The equations are second order (meaning that they involve differentiation of a quantity twice) because the velocity itself is the derivative with respect to time of the position vector, and the angular momentum vector contains time derivatives of angles that specify the orientation of the rigid body with respect to the fixed reference frame. From the form of the equations, we see the symmetry: The linear momentum vector $\vec{\mathbf{P}}$ corresponds to the angular momentum vector $\vec{\mathbf{H}}$, the resultant of the forces corresponds to the resultant of the moments.

The key issues to keep in mind are:

- The equations hold in this form if the frame of reference for the vectors (velocity, force, angular momentum, and moment) is **inertially fixed.** For the case of a skier moving on a slope, this means that the unit vectors defining the inertial frame are fixed to the slope at some convenient point.

- The equation of the center of mass defines how the body CM moves in space and essentially can be considered to define the path of a particle (no physical dimensions, but having all the body mass M). This equation describes approximately the path that the skier's belly button follows down the slope.

- The external physical (motive) forces acting on the skier are:

    * gravity
    * interactions between the skis and the snow
    * air resistance on the skier's body/skis/poles (air drag)
    * interactions between the poles and the snow, whenever the poles touch the snow

- Gravity always acts through the skier/ski center of mass

- The interaction forces between skis and snow will act normal to the ski surface, longitudinally along the surface, and laterally against the side wall and edges. The exact picture will vary depending on what is going on at the moment. The physical mechanisms we can consider acting are friction, shear forces as the edges of the skis shave away the snow surface, as well as just simple interactions acting perpendicular to a section of the ski(s).

- Air resistance will be proportional to the speed (magnitude of the velocity) squared, the surface area of the body, and the density of the air.

- These equations describe the **local behavior** of the system (at one particular, but general, instant of time at a particular, but general point in space).

- To work with these equations, we must introduce a specific reference frame defined by suitable unit vectors. The vector form is nice and compact, but to do anything with the equations, we need to coordinatize in a chosen reference frame. Then, the form taken will change depending on the reference frame we have selected.

A.2 THE TRUE NATURE OF "INERTIAL FORCES"

First, I will develop the equations governing the motion of the CM. The purpose is to show the origin of the so-called inertial forces. The root of the difficulty with the concept of "real" versus "fictional or inertial forces" lies with D'Alembert, another French mathematician of the eighteenth century. There is considerable merit *in the concept,* which comes to the forefront when one works with analytical mechanics as formulated by Lagrange. However, when applied in the context of Newtonian formulations, it is a constant source of confusion and error for students of dynamics at all levels. (As will be seen, first one must be careful as to what sign should be used, and second, one should be careful not to include the same effect twice!).

First, I will rewrite the equations as follows by subtracting $\frac{d(m\vec{V})}{dt}$ from both sides of the original equation describing the motion of the CM:

$$0 = \sum\vec{F} - \frac{d(m\vec{V})}{dt}$$

The next step is to *define* "inertial force" as

$$\vec{F}_{\text{inertial}} = -\frac{d(m\vec{V})}{dt}$$

then the equation of motion of the center of mass becomes simply:

$$0 = \sum\vec{F} + \vec{F}_{\text{inertial}}$$

The equation now is exactly in the same form as used in statics (when no motion of the system occurs). Namely, the vector sum of all acting forces, external as well as inertial, is zero and the (extended) force system is in equilibrium. However, as a by-product, the realm of confusion in mechanics is launched.

Why? Because we *sense* things in a coordinate frame that is attached to our bodies, *not* in an inertial reference frame! So we have a paradox: From analysis we deduce that the "inertial forces" are "fictional" because they are nothing but a redefinition of the time rate of change of momentum with a negative sign added, but from personal experience and sensations, we *feel* the "inertial forces" in the same sense that we feel someone pulling on us!

So how does this happen? Let's return to the original form of the equation for the center of mass. Introduce a reference frame (for the present it is arbitrary) that is now **moving and accelerating** with respect to a fixed inertial reference frame. I call this the $\hat{\mathbf{e}}_1, \hat{\mathbf{e}}_2, \hat{\mathbf{e}}_3$ reference frame. For example, the illustration of the general motion of a rigid body, Figure 4.4 , page 4.7, shows such a frame.

The position of the center of mass with respect to inertial space, but expressed in this moving frame, is:

$$\vec{\mathbf{R}} = \mathbf{R}_1\hat{\mathbf{e}}_1 + \mathbf{R}_2\hat{\mathbf{e}}_2 + \mathbf{R}_3\hat{\mathbf{e}}_3 = \sum_{i=1}^{3}\mathbf{R}_i\hat{\mathbf{e}}_i$$

where the $\mathbf{R}_i$ are just scalars (but they will change in time). The velocity with respect to inertial space (again expressed in terms of the moving frame) then becomes:

$$\vec{\mathbf{V}} = \frac{d\vec{\mathbf{R}}}{dt} = \sum_{i=1}^{3}\left[\frac{d\mathbf{R}_i}{dt}\right]\hat{\mathbf{e}}_i + \sum_{i=1}^{3}\mathbf{R}_i\frac{d\hat{\mathbf{e}}_i}{dt} = \sum_{i=1}^{3}\left[\frac{d\mathbf{R}_i}{dt}\hat{\mathbf{e}}_i + \mathbf{R}_i\frac{d\hat{\mathbf{e}}_i}{dt}\right]$$

since not only are the scalar "measure numbers" $\mathbf{R}_i$ of $\vec{\mathbf{R}}$ changing in time but the unit vectors $\hat{\mathbf{e}}_i$ are also. (This step requires one to know the rules for differentiating vectors, so if you don't know these, take the results as given. I don't have the space here to derive these rules). Then we must repeat the process one more time since we need the time derivative of the velocity in the equation of motion. Skipping the intermediate steps, the final result is:

$$\frac{d\vec{\mathbf{V}}}{dt} = \sum_{i=1}^{3}\left[\frac{d^2\mathbf{R}_i}{dt^2}\hat{\mathbf{e}}_i + 2\frac{d\mathbf{R}_i}{dt}\frac{d\hat{\mathbf{e}}_i}{dt} + \mathbf{R}_i\frac{d^2\hat{\mathbf{e}}_i}{dt^2}\right]$$

Now, the time rate of change of a unit vector (which is free to move in inertial space) with respect to inertial space is equal to the vector cross product of the angular velocity of the unit vector with itself (again, a special result that can be proven). So if I define $\vec{\Omega}$ to be this angular velocity with units of radians per second (also a vector) then:

$$\frac{d\hat{\mathbf{e}}_i}{dt} = \vec{\Omega}\times\hat{\mathbf{e}}_i$$

and the second derivative of $\hat{\mathbf{e}}_i$ becomes:

$$\frac{d^2\hat{\mathbf{e}}_i}{dt^2} = \frac{d\vec{\Omega}}{dt}\times\hat{\mathbf{e}}_i + \vec{\Omega}\times\left[\vec{\Omega}\times\hat{\mathbf{e}}_i\right]$$

and the expression for $\frac{d\vec{\mathbf{V}}}{dt}$ becomes

$$\frac{d\vec{V}}{dt} = \sum_{i=1}^{3}\left[\frac{d^2R_i}{dt^2}\vec{e}_i + 2\frac{dR_i}{dt}\vec{\Omega}\times\hat{e}_i + R_i\left[\frac{d\vec{\Omega}}{dt}\times\hat{e}_i + \vec{\Omega}\times\left[\vec{\Omega}\times\hat{e}_i\right]\right]\right]$$

So now the equation of motion looks pretty messy:

$$m\sum_{i=1}^{3}\left[\frac{d^2R_i}{dt^2}\hat{e}_i + 2\frac{dR_i}{dt}\vec{\Omega}\times\hat{e}_i + R_i\left[\frac{d\vec{\Omega}}{dt}\times\hat{e}_i + \vec{\Omega}\times\left[\vec{\Omega}\times\hat{e}_i\right]\right]\right] = \Sigma\vec{F}$$

The stuff on the right involves only mass times the acceleration of the center of mass, although expressed in the body centered moving reference frame defined by the unit vectors $\vec{e}_i$. To aid in thinking about the problem, one can identify these with the principal planes of symmetry of the human body: The longitudinal axis, the lateral axis and the transverse axis, for example, as is suggested by the sketch introducing the moving reference frame.

Now I can identify the different terms that arise due to the fact that I have coordinatized the kinematics in a moving reference frame:

$\frac{d^2R_i}{dt^2}\hat{e}_i$: the acceleration with respect to the moving reference frame

$2\frac{dR_i}{dt}\vec{\Omega}\times\hat{e}_i$: Coriolis acceleration

$R_i\frac{d\vec{\Omega}}{dt}\times\hat{e}_i$: tangential acceleration

$R_i\vec{\Omega}\times\left[\vec{\Omega}\times\hat{e}_i\right]$: centripetal acceleration

When multiplied by the mass **m** and moved to the right side of the equation above with the corresponding change of sign from + to - , these contribute the so-called "**inertial forces**" to the discussion of dynamics:

$-m\frac{d^2R_i}{dt^2}\hat{e}_i$: This "inertial force" does not have a specific name attached to it

$-2m\frac{dR_i}{dt}\vec{\Omega}\times\hat{e}_i = -2m\vec{a}_c = \vec{F}_c$: Coriolis force

$-mR_i\frac{d\vec{\Omega}}{dt}\times\hat{e}_i = -m\vec{a}_T = \vec{F}_T$: Tangential force (although this term is rarely used, even by physicists)

$-mR_i\vec{\Omega}\times\left[\vec{\Omega}\times\hat{e}_i\right] = -m\vec{a}_{centripetal} = \vec{F}_{centrifugal}$: Centrifugal force

Because the sign changed from + to - in the definition of this "inertial force", the term changed from "centripetal" to "centrifugal". The term centripetal means "moving to or tending to move **toward** a center and the term centrifugal means "moving or tending to move **away from** a center." Notice that the terms imply movement or tendency toward movement, a description of kinematics, not forces. It is interesting to note that the "Coriolis force" as well as the "tangential force" did not acquire new names just because of the change in sign in the definition of the "inertial forces", only "centripetal" changed to "centrifugal". However, thanks to D'Alembert we now live with the concept of "inertial forces" as well as the confusing terminology (although as we have seen, Newton himself is partly to blame, since he coined the term "centripetal force"!)

Why is this a problem? Because in the D'Alembert form of the equations of motion, the key concept of cause and effect is lost. In the original Newton form, the **physical motive forces cause motion** so some **external, physical force causes centripetal acceleration.** The confusion then really gets going when the generic term "centripetal force" gets applied to whatever the actual physical force is that is acting towards the center of the (curving) path. In the case of skiing, components of the ski/snow interaction forces provide the centripetal force. Since cause and effect requires something to happen first before something else happens this distinction is critical to the understanding of dynamics.

Now I apply these general results to the skier. The moving coordinates are now chosen as *body fixed* (to the skier) as indicated schematically on Figure 4.4, page 4.7. Also, for ease of discussion, I consider the motion to be in a plane. This assumption restricts the angular velocity to a simple rotation about the vertical axis indicated by the unit vector $\hat{\mathbf{e}}_2$.

For the coordinates chosen and the assumed motion (skier traveling in curving - but not necessarily circular - path in the plane of the slope) the angular velocity is simply:

$\vec{\Omega} = \Omega\hat{\mathbf{e}}_2$ and the equation of motion is (written in D'Alembert form):

$$m\sum_{i=1}^{3}\frac{d^2R_i}{dt^2}\hat{\mathbf{e}}_i = \sum\vec{F} + \vec{F}_{coriolis} + \vec{F}_{tangential} + \vec{F}_{centrifugal}$$

Now, on the left side of the equation (which looks just like the standard mass times acceleration term) I can identify the acceleration terms relative to what the person is feeling in the body reference axes:

$\frac{d^2R_1}{dt^2} = \mathbf{a}_1$, the magnitude of the acceleration in the lateral direction (side-to-side).

$\frac{d^2R_2}{dt^2} = \mathbf{a}_2$, the magnitude of the acceleration in the longitudinal direction (up-down)

$\frac{d^2R_3}{dt^2} = \mathbf{a}_3$, the magnitude of the acceleration in the transverse direction (front-to-back)

Now, write the equations of motion as follows:

$$\mathbf{m a_1 \hat{e}_1 + m a_2 \hat{e}_2 + m a_3 \hat{e}_3 = \Sigma \vec{F} + \vec{F}_{coriolis} + \vec{F}_{tangential} + \vec{F}_{centrifugal}}$$

The left side of this equation now looks like the usual mass times acceleration in conventional Newton form. On the right side, are not only the real applied external motive forces of gravity, air resistance and ski-snow interactions, but the "inertial forces" as well. Note that there are three of them. As a rule, for the rates and characteristic distances involved in ski turns, only the centrifugal term is sensed. So we come to the explanation of the paradox: Are "inertial forces" real or fictional? In the true definition of what (motive) force means in the Newtonian sense, there are no inertial forces, just some different forms of the basic equations of motion as a consequence of coordinate choices. Note that these forms will change significantly depending on the form of the moving coordinates one chooses; that is, "centrifugal forces" do not always act strictly outward from the center of any fixed circle. From a physical sensory point of view, we do feel these as real forces. Something *is* pulling us outward according to our sensors in the body!

A.3 ANALYSIS OF STRAIGHT RUNNING AND TERMINAL VELOCITY

In general it is difficult to apply these equations to skiing. In one case however, we can get explicit results: The problem of analyzing straight running down a constant slope, say the problem of speed skiing. To do this, I will use an inertial reference frame with the origin fixed to the start, on a slope of constant angle theta (θ). I define the appropriate vectors as shown in Figure A.1.

The equation of motion I need is:

$$\frac{d(m\vec{V})}{dt} = \frac{d\vec{P}}{dt} = \Sigma \vec{F}$$

The momentum expressed in the $\hat{k}_1, \hat{k}_2$ reference frame is:

$\vec{P} = mV\hat{k}_2$ where **V** is the speed (magnitude of the velocity)

The external forces acting will be gravity, which is:

$$\vec{F}_{gravity} = -mg\cos\theta\hat{k}_1 + mg\sin\theta\hat{k}_2$$

and snow friction, which I assume to be proportional to the normal pressure exerted by the skier against the snow surface:

$$\vec{F}_{snow} = -\mu mg\cos\theta\hat{k}_2$$

Then, I assume that the air drag on the body is proportional to the speed squared and acts opposing the direction of motion (this is a good assumption for many air drag problems e.g. air drag on aircraft):

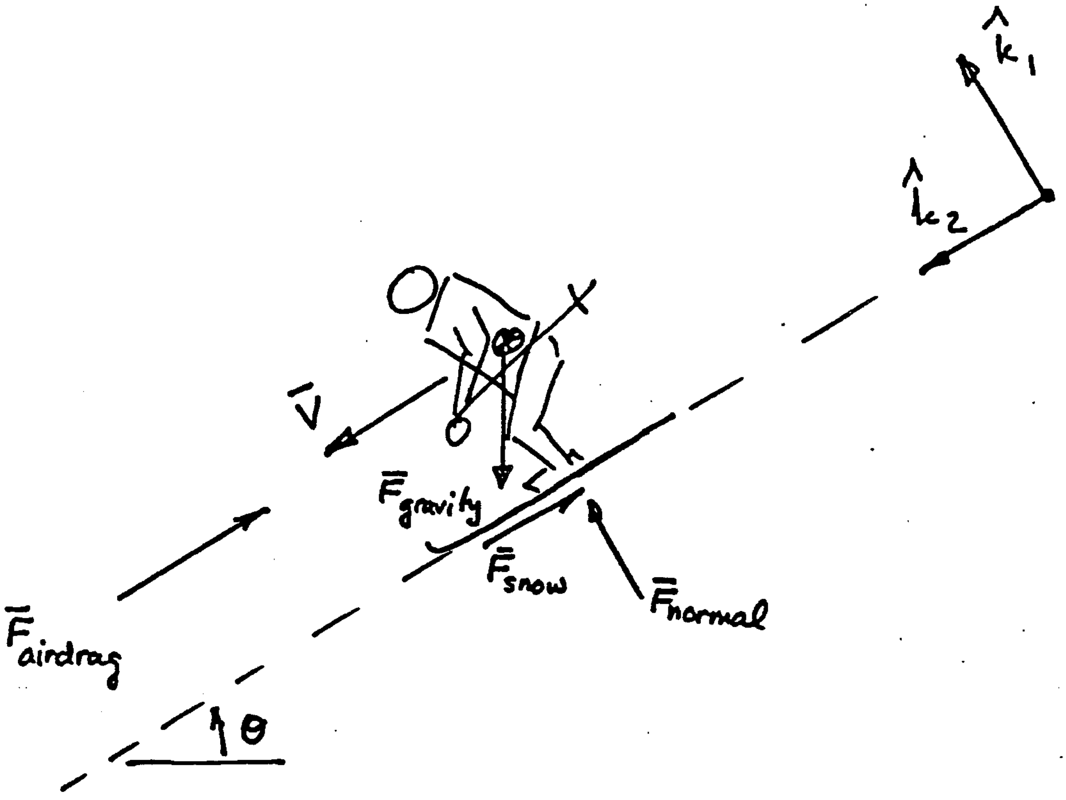

FIGURE A.1 GEOMETRY OF THE STRAIGHT RUNNING PROBLEM

$$\vec{F}_{airdrag} = -\frac{1}{2} C_d \rho A V^2 \hat{k}_2$$

here, C_d is the drag coefficient for the skier (usually measured in the wind tunnel), ρ is the air density at the competition site, A is a reference area (usually the frontal area of the skier).

Last, I need to include the normal snow reaction on the skis:

$$\vec{F}_{normal} = N\hat{k}_1$$

If the snow is soft, it will also offer "form resistance" which is not frictional in nature (i.e. the snow resists the tip of the ski moving against and over it, this is the force required to pack the snow down). For hard snow typical of speed events, this effect can be neglected. Putting all this together I get:

$$M\frac{dV}{dt}\hat{k}_2 = -mg\cos\theta\hat{k}_1 + mg\sin\theta\hat{k}_2 - \mu mg\cos\theta\hat{k}_2 - \frac{1}{2}C_d\rho AV^2\hat{k}_2 + N\hat{k}_1$$

Equality implies that the coefficients of $\hat{k}_1, \hat{k}_2$ on each side of the equation are equal, so the vector equation becomes two regular (scalar) equations:

$$M\frac{dV}{dt} = mg\sin\theta - \mu mg\cos\theta - \frac{1}{2}C_d\rho AV^2$$

$$0 = N - mg\cos\theta$$

Notice that the second equation just tells us that the snow pushes as hard on the ski as the ski pushes on the snow.

To proceed, it is convenient to define two constants (depending on gravity, the steepness of the slope, coefficient of friction of the snow, the skiers mass, coefficient of drag and frontal area):

$$\kappa_1 = g[\sin\theta - \mu\cos\theta]$$

$$\kappa_2 = \frac{1}{2m}C_d\rho A$$

Then the equation of motion assumes the simple form:

$$\frac{dV}{dt} = \kappa_1 - \kappa_2 V^2$$

From this equation I can immediately write down the expression for the terminal velocity which occurs when $\frac{dV}{dt}$ goes to zero:

$$V_t = \sqrt{\frac{\kappa_1}{\kappa_2}} = \sqrt{\frac{2mg(\sin\theta - \mu\cos\theta)}{C_d \rho A}}$$

I can also integrate the differential equation and find the speed as a function of time:

$$dt = \frac{dV}{\kappa_2\left[\frac{\kappa_1}{\kappa_2} - V^2\right]}$$

$$t + c = \frac{1}{2\kappa_2\alpha}\log\left[\frac{\alpha + V}{\alpha - V}\right]$$

where $\alpha = \sqrt{\frac{\kappa_1}{\kappa_2}}$ and the constant $c = \frac{1}{2\sqrt{\kappa_1\kappa_2}}\log(1)$. The speed approaches the terminal value asymptotically.

A.4 WORK AND ENERGY

The relationship of work and energy can be derived mathematically from Newton's Second Law. The following bit of mathematical juggling uses the rules (and some allowable tricks) of differential and integral calculus.

Recall that the equation of motion was expressed as the time rate of change of momentum is equal to the resultant of the external forces:

$$\frac{d(m\vec{V})}{dt} = \frac{d\vec{P}}{dt} = \Sigma\vec{F} = \vec{F}_R$$

For convenience of notation, I replace the summation of the forces by $\vec{F}_R$ which I call the resultant, and use $\vec{P}$ for the momentum. We follow the path of the body (still thought of as a particle) along some general curve C and consider two time points t_1 and t_2 when the body is at the points A and B on the path C as shown on Figure 5.1, page 5.2.

Vector calculus allows me to form something called the dot product of both sides of the equation of motion with a small displacement vector $d\vec{S}$. The dot product operation is the projection of one vector onto another defined by the product of the magnitudes times the cosine of the angle between them.

$$\frac{d\vec{P}}{dt} \bullet d\vec{S} = \vec{F}_R \bullet d\vec{S}$$

Then, I integrate both sides of this expression over the path C from point A to point B:

$$\int_{t_1}^{t_2} \frac{d\vec{P}}{dt} \bullet d\vec{S} = \int_{t_1}^{t_2} \vec{F}_R \bullet d\vec{S}$$

always pass regardless of how the forces may be turned, provided they remain parallel. The CG of a body (or a system of bodies) is defined as the centroid of the forces of gravitation acting upon all particles thereof. The center of mass of a body is a point of the body such that the total mass moment (total mass times distance to a fixed point) is equal to the sum of the individual mass moments of all the particles that make up the body. The reason that the CG and the CM are slightly different lies in the requirement that the forces acting be parallel. For all practical purposes, this can be assumed to be the case for the forces of gravity acting on a relatively small body such as the skier.

The equations governing the motion about the CM determine what happens to our orientation in space, and in particular, our orientation relative to the slope. Do we or do we not remain upright as we ski down the slope?

Recall the equation governing the motion about the CM:

$$\frac{d\vec{H}}{dt} = \Sigma\vec{M}$$

This equation tells us that *if* the resultant moment of all the external forces about the CM is zero, then the angular momentum is zero. Since the inertia properties of the body do not change, this means that the total angular velocity remains constant. An alternative and useful way to think about this is to consider the governing equation resolved into its three components along the body reference axes. From considering the equations for each axis we can deduce that if there is no moment component about that axis, then if there is no component of rotation about that axis, none can be created.

We know that if the lines of action of all the external forces pass through the center of mass, there is no moment. If in addition there is no component of angular velocity about a given axis, such as the fore-aft axis or the right-left lateral axis, the body will not tip about either axis. We are free to have a component of angular velocity for the "vertical" axis and some non-zero moment about that axis. This allows some body rotation relative to the fixed reference as we ski down the hill. But the essential result is this: IF the lines of action of the ski/snow reaction forces and air drag forces pass through the CM no tipping of the body will occur.