Anterior Cruciate Ligament Forces in Alpine Skiing

Walter Herzog and Lynda Read

The purpose of this study was to estimate cruciate ligament forces in Alpine skiing during a movement that has been associated with anterior cruciate ligament (ACL) tears. Resultant knee joint forces and moments were obtained from two skiers during a World Cup Downhill race using an inverse dynamics approach and a 2-D bilaterally symmetric system model. It was found that ACL forces were typically small for both skiers throughout the movement analyzed because quadriceps forces prevented anterior displacement of the tibia relative to the femur at the knee joint angles observed. However, for about 10 ms, loading conditions in the knee joint of Subject 2 (who displayed poor form) were such that large ACL forces may have been present. These particular loading conditions were never observed in Subject 1, who displayed good form. Since neither of the skiers was injured, it is not possible to draw firm conclusions about isolated ACL tears in Alpine skiing from the data at hand.

The incidence of anterior cruciate ligament (ACL) injuries in Alpine skiing has increased in the past 2 decades (Bechtel, Ellman, & Jordon, 1984; Feagin et al., 1987; Hauser & Schaff, 1987; Howe & Johnson, 1982; Johnson, Ettlinger, & Shealy, 1991; McConkey, 1986). This increase has been associated at least partly with changes in the design of ski boots and the design and release settings of bindings (Bally, Boreiko, Bonjour, & Brown, 1989; Figueras et al., 1987; Johnson, Ettlinger, Campbell, & Pope, 1980; Johnson, Ettlinger, & Shealy, 1989; Johnson et al., 1991). For example, the ski boots have become higher and stiffer in the past years, thus increasing the potential for transmitting forces directly from the skis to the knee joints (Bechtel et al., 1984; Ettlinger, 1986; Hauser & Schaff, 1987; Johnson et al., 1991).

Isolated ACL tears have only been reported most recently for Alpine skiers, and they appear to be a by-product of changes in the design of boots. This injury has been reported most often for male, high-speed skiers and for Alpine competitors (Figueras et al., 1987; Hauser & Schaff, 1987; McConkey, 1986). One particular movement that has been associated with isolated ACL tears is when a skier lands in a sitting-back position after an airborne phase, and then

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tries to recover from this fallen-back position (Bally et al., 1989; Figueras et al., 1987). In this situation, the bindings typically do not release, and the skiers report a "snap" or "pop" in their knees, either as they are forced into a hyperflexed knee joint position or as they try to recover from the hyperflexed knee joint position by contracting the knee extensor muscles powerfully (Figueras et al., 1987).

Although isolated ACL injuries in Alpine skiing have been described in the literature (Ekeland & Thoresen, 1987; Shino, Horibe, Nagano, & Ono, 1987), the precise loading conditions and the mechanisms associated with this injury have not been studied using experimental data of the condition of interest. It has been speculated that the ski boot pushing forward on the tibia may preload the ACL (Bally et al., 1989). This preload coupled with a violent contraction of the quadriceps muscle group to maintain balance is believed to be instrumental to the tearing of the ACL (Feagin et al., 1987; McConkey, 1986, 1987). It has also been suggested that increased strength of the hamstring muscles may aid in the prevention of this injury (Figueras et al., 1987).

The purpose of this study was to estimate cruciate ligament forces in Alpine skiing during a movement that has been associated with ACL tears. It was hypothesized that an understanding of the loading conditions in and around the knee joint for a particular movement associated with ACL tears may help identify the mechanisms of injury and so may yield important findings for prevention of this injury.

Methods

In order to quantify internal forces at the knee joint during Alpine skiing it was necessary (a) to calculate resultant knee joint forces and moments during the movement of interest, (b) to describe the variable geometry of the force-carrying structures of the knee joint as a function of knee joint angle, and (c) to calculate the internal forces from the external joint resultants (obtained in Part a) and the appropriate joint geometry (obtained in Part b). Determination of the variable knee joint geometry and calculation of the resultant external knee joint forces and moments have been described elsewhere (Herzog & Read, 1993; Read & Herzog, 1992, respectively) and will only be presented briefly. Calculation of the internal forces acting in and around the knee joint during a landing movement in Alpine skiing was performed with the so-called distribution approach (Crowninshield & Brand, 1981) and will be presented in detail.

Calculation of Knee Joint Resultants

Data were calculated from male Alpine ski racers during training and competition at a World Cup downhill event. Skiers were filmed from the side with high-speed cinematography (Locam, 200 frames/s) at a place where the movement of interest had been observed in training runs preceding the data collection sessions.

Results from two Alpine skiers who landed symmetrically on left and right skis as assessed subjectively from the film records will be presented. One skier performed the movement in "good form"; the other skier performed the movement in "poor form," which means the skier was forced into a fallen-back
position but was able to recover and regain balance (Figure 1). Resultant knee joint forces and moments were calculated with a two-dimensional inverse dynamics approach (Andrews, 1974) and segmentation method (Hay, 1985) starting at the hand segment and working distally until the resultants at the knee joint (defined as the lateral contact point between tibia and femur) were obtained. The mass of the poles was ignored, the poles were not in contact with the snow during the time interval of interest, and the forces associated with air resistance were neglected since their influence on resultant knee joint forces and moments was found to be small (Read & Herzog, 1992).

Kinematic data were differentiated with a quintic spline approximation of the raw data with a smoothing factor determined by error estimates of each data

Figure 1 — Stick figure diagrams of the movements analyzed. Subject 1 (top) performed the movement of interest in a well-controlled manner, whereas Subject 2 (bottom) executed the movement with considerable difficulties. *Note.* "External Loading at the Knee Joint for Landing Movements in Alpine Skiing" by L. Read and W. Herzog, 1992, *International Journal of Sport Biomechanics*, 8, p. 64. Reprinted by permission.
point (local error) and the entire trial (global error estimate) (Read & Herzog, 1992; Yeadon, 1984). When solving the inverse dynamics problem going from the hand to the shank segment, one encounters a problem when assigning hip joint resultants to the left and right hip joints. This was done assuming an equal distribution of the hip joint resultants, which may be interpreted as simulating a perfectly symmetrical landing of the skier.

**Determination of Knee Joint Geometry**

In order to calculate internal forces in and around the knee joint during Alpine skiing, it was necessary to determine the lines of action and moment arms of the major force-carrying structures crossing the knee joint as a function of knee joint configuration. Lines of action and moment arms were determined for all hamstring and quadriceps muscles and for the two cruciate and the two collateral ligaments and were expressed in a tibia-embedded reference (Figure 2). The gastrocnemius muscle was not incorporated into the model, since its contribution to the movement of interest was considered to be of minor importance (Read & Herzog, 1992). The knee joint center was defined as the lateral contact point of tibia and femur (Nisell, Nemeth, & Ohlsen, 1986). Data were determined using five unembalmed cadaver specimens, and all attachment sites of ligaments and muscles were digitized with a three-dimensional perceptor.

Lines of action of all ligaments and all muscles except the knee extensor

![Figure 2 - Tibia-embedded reference system with its origin at the knee joint (lateral contact point of tibia and femur; Nisell et al., 1986). The positive y-axis is defined from the lateral malleolus to the knee joint center, and the x-axis is perpendicular to the y-axis through the knee joint center. Note. From "External Loading at the Knee Joint for Landing Movements in Alpine Skiing" by L. Read and W. Herzog, 1992, International Journal of Sport Biomechanics, 8, p. 65. Reprinted by permission.]
group were defined by a straight line joining origin and insertion sites. The line of action of the knee extensor muscles was defined by the patellar tendon. Moment arms were calculated as the perpendicular distance from knee joint center to the line of action of the structure of interest. This was done for knee joint angles ranging from 0° (fully extended) to 130° (fully flexed) at increments of about 10°. For this particular study, data from one cadaver specimen were selected for analysis using a standard regression approach that related lines of action and moment arms of the structures of interest to knee joint angles. The selected cadaver was sex-matched and corresponded best in terms of height and weight with the two Alpine skiers selected for internal knee joint force analysis.

**Determination of Internal Knee Joint Forces**

Internal knee joint forces during landing movements in Alpine skiing were calculated by solving the distribution problem using the reduction method (Andrews, 1982; Crowninshield & Brand, 1981). This approach involves the distribution of the resultant joint forces and moments to the forces and moments produced by force-carrying structures in the vicinity of the knee joint. Structures that were considered to transmit nonnegligible forces were the muscles, ligaments, and bones that make up the knee joint. Therefore, the joint equipollence equations can be written as

\[
F = \sum_{i=1}^{M} f_i^m + \sum_{j=1}^{L} f_j^l + \sum_{k=1}^{B} f_k^b
\]

\[
M = \sum_{i=1}^{M} (r_i^m \times f_i^m) + \sum_{j=1}^{L} (r_j^l \times f_j^l) + \sum_{k=1}^{B} (r_k^b \times f_k^b)
\]

where \( F \) and \( M \) are the variable resultant knee joint force and moment acting on the shank segment, respectively, and \( f \) and \( r \) indicate the force and location vectors, respectively, and the superscripts \( m, l, \) and \( b \) refer to muscles, ligaments, and bones, respectively.

The muscles, ligaments, and bones included in the present knee joint model were the quadriceps femoris and hamstring muscle groups, the anterior and posterior cruciate and the lateral and medial collateral ligaments, and the tibia and femur bones. The forces transmitted by other potential force-carrying structures (e.g., the joint capsule) were assumed to be negligible for the movement studied here. Muscles and ligaments were modeled as straight lines through the centroids of the attachment areas. A straight line approach becomes problematic for the hamstring muscles toward extended knee joint angles but was adequate for the flexed knee configurations studied here (Herzog & Read, 1993). The line of action of the quadriceps muscle group was represented by the patellar tendon.

The knee joint has two tibiofemoral contact areas: the medial and lateral femoral condyles on the medial and lateral tibial plateaus, respectively. The distributed bony contacts were replaced here by a single resultant contact force acting at the contact point of the lateral femoral condyle and the lateral tibial plateau (i.e., the knee joint center; Nisell et al., 1986) and directed perpendicularly to the tibial plateau.

Since the knee joint model was two-dimensional in the flexion–extension plane, Equations 1 and 2 yield three scalar equations: two force equations and
one moment equation. After the knee joint resultants, \( F \) and \( M \), were quantified, using the inverse dynamics approach, and all moment arms and lines of action were determined using data from the cadaver study, there were potentially \( M + L + B \) scalar unknowns (Equations 1 and 2). These unknowns correspond to the magnitudes of the forces of muscles (\( M = 2 \)), ligaments (\( L = 4 \)), and bony contacts (\( B = 1 \)), yielding a total of seven unknowns. A system containing three equations and seven unknowns is underdetermined and has no unique solution. In order to make the system determinate, the number of unknowns was reduced from seven to three through the following assumptions:

- Forces in knee flexor muscles (\( f_h \)) were assumed to be a known fraction (\( k \)) of the forces in knee extensor muscles (\( f_p \)).
  \[
  f_h = k f_p; \quad \text{for } 0 \leq k \leq 1.0
  \]  
  Since the value of \( k \) in Equation 3 is not known in reality, \( k \) was varied between 0 (no hamstring activity) and 1.0 (considered to be the maximal hamstring activity).

- Forces in the posterior cruciate ligament were assumed to be zero when forces were present in the ACL and vice versa (Butler, Noyes, & Grood, 1980).

- Forces in the collateral ligaments (\( f_{\text{coll}} \)) were assumed to be a known fraction (\( v \)) of the cruciate ligament forces (\( f_{\text{cruc}} \)).
  \[
  f_{\text{coll}} = v f_{\text{cruc}}; \quad \text{for } 0 \leq v \leq 0.5
  \]  
  Since the value of \( v \) in Equation 4 is not precisely known, \( v \) was varied between 0 (no collateral ligament forces) and 0.5. This corresponds to a small component of collateral ligament forces parallel to the tibial plateau compared to the corresponding forces of the cruciate ligaments since the collateral ligaments tend to run almost perpendicularly to the tibial plateau for the joint configurations considered here (e.g., Ahmed, Hyder, Burke, & Chan, 1987; Butler et al., 1980; Herzog & Read, 1993).

Additionally, moments produced by ligaments about a transverse axis through the knee joint were initially assumed to be negligible compared to moments produced by muscles (Herzog & Read, 1993).

With these assumptions accepted, the distribution problem became determinate and could be represented by Equations 3–6

\[
F = f_{\text{cruc}} + f_{\text{coll}} + f_p + f_h + f_b
\]  

\[
M = (r_p \times f_p) + (r_h \times f_h)
\]  

where \( F \) and \( M \) are the variable resultant knee joint force and moment, respectively, \( f \) and \( r \) are force and location vectors, and subscripts \( p, h, \) and \( b \) refer to patellar tendon, hamstring muscles, and bony contact, respectively. Vectors are indicated by boldface type.

Initially, Equations 3 to 6 were solved for the case where the collateral ligaments and antagonistic forces did not contribute to the resultant knee joint force and moment, that is, \( k = 0 \) and \( v = 0 \). After that, Equations 3 to 6 were solved for a series of cases with varying values for \( k \) and \( v \) within the limits
imposed in Equations 3 and 4. In the first step of the distribution approach, Equation 6 was used to calculate $f_p$ (and, if applicable, $f_b$ using Equation 3 for a given value of $k$). In a second step, Equation 5 was used to solve for the remaining unknowns by determining which of the cruciate ligaments was transmitting force (based on the direction of the component of the resultant knee joint force acting on the shank and parallel to the tibial plateau), and then by determining the magnitudes of $f_{cne}$, $f_{coll}$, and $f_b$ by solving the three scalar equations that can be derived from Equations 4 and 5, simultaneously. The directions of the force vectors of $f_{cne}$, $f_{coll}$, and $f_b$ were known at any instant in time (i.e., any knee joint configuration).

## Results

Figures 3 and 4 show the resultant knee joint moments (which must be provided by muscular forces) and forces, respectively, for the two skiers analyzed, and Figures 5 and 6 show the corresponding components of the resultant knee joint forces that are parallel (x) and perpendicular (y) to the tibial plateau. Subject 1 refers to the skier who performed the movement in good form; Subject 2 refers to the skier who performed the movement in poor form (Figure 1). The resultant joint moment of Subject 2 acting on the shank was more variable than that of Subject 1 (Figure 3) and, furthermore, reached positive values at approximately

![Graph](image)

Figure 3 — Resultant external knee joint moments as a function of time for Subjects 1 and 2. Flexor moments are positive and extensor moments negative.
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RESULTANT JOINT FORCE (BW)

**Figure 4** — Resultant external knee joint forces as a function of time for Subjects 1 and 2 in units of body weight (BW).

0.13 s after both skis were flat on the ground after landing (t = 0 s). This positive moment is associated with a resultant knee flexor torque, an unsuspected finding for a skier who struggles to extend his knee joints and regain balance after a bad landing from a jump.

Resultant knee joint forces acting on the shank were similar in both subjects for the first 200 ms after landing (Figure 4). After 200 ms, Subject 1 left the field of view of the fixed camera. The resultant joint force for Subject 2 continued to decline to about 0.5 body weight over the next 50 ms and then started to increase again just before he left the field of view.

The components of the resultant knee joint force that were parallel to the tibial plateau were mostly positive (Figure 5) and the components that were perpendicular to the tibial plateau were always negative (Figure 6), indicating a downward and anterior-directed force from the thigh onto the shank. Negative (or posterior) forces in the parallel component occurred at the very beginning and very end of the movement analyzed for Subject 1, and occurred in the midphase (0.11 to 0.16 s) for Subject 2. Maximal forces in the parallel component of the resultant knee force approximated 0.5 times body weight and reached 1.25 and 1.5 times body weight for the perpendicular component (Figures 5 and 6).

Patellar tendon forces were more variable in Subject 2 than Subject 1 and reached values for Subject 2 (almost 9,000 N at t ~ 0.04 s, Figure 7) that must be considered at the upper limit of possible quadriceps forces (Herzog, Hasler, &
Abrahamse, 1991), even for an extremely strong athlete, such as a World Cup downhill skier. At $t \sim 0.13$ s, the estimated patellar tendon forces of Subject 2 became zero, since the corresponding resultant joint moment was in the flexor direction at this precise instant in time. One may speculate that the knee flexor moment at this instant in time (i.e., $\sim 0.13$ s, Subject 2) was caused by contraction of the hamstring muscles. This speculation does not appear feasible when considering that the skier tried to recover from a hyperflexed knee joint position.

Immediately after Subject 1 landed, it appears that his ACL was loaded for a very short period of time, followed by loading of the posterior cruciate ligament for the remainder of the movement analyzed (Figure 8). Except for a single instant in time analyzed ($t = 0.132$), forces in the cruciate ligaments appeared to be consistently associated with the posterior cruciate ligament in Subject 2 (Figure 9). At precisely $t = 0.142$ s, the posterior cruciate ligament forces determined for Subject 2 reached a peak value exceeding 3,000 N. This instant in time coincides with the peak resultant knee flexor moment (Figure 3) and the loss of quadriceps force (Figure 7).

Figures 10, 11, and 12 show the patellar tendon forces, posterior cruciate ligament forces, and bony contact forces for simulation of collateral ligament

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**Figure 5** — Component of the resultant knee joint force acting parallel to the tibial plateau for Subjects 1 and 2 in units of body weight (BW). Positive forces are directed anteriorly. Note. From “External Loading at the Knee Joint for Landing Movements in Alpine Skiing” by L. Read and W. Herzog, 1992, *International Journal of Sport Biomechanics, 8,* p. 68. Reprinted by permission.
forces (Equation 4, $v = 0.5$, and Equation 3, $k = 0$, Simulation 1) and for simulation of muscular activity provided by the hamstring muscles (Equation 3, $k = 0.2$, and Equation 4, $v = 0$, Simulation 2) for Subject 2. Simulation of collateral ligament forces as a fixed fraction of the cruciate ligament forces did not change internal muscular, ligamentous, or bony contact forces dramatically. Simulation of hamstring forces increased internal forces substantially (Figures 10–12). In particular, posterior cruciate ligament forces were nearly tripled at many instants in time for simulations including hamstring forces compared to the initial calculations where hamstring forces were assumed to be zero.

**Discussion**

The skiing movement analyzed in this study has been associated with isolated ACL tears in competitive skiers (Bally et al., 1989; Figueras et al., 1987; Hauser & Schaff, 1987; McConkey, 1986). During the training runs and the actual World Cup downhill race, no such injuries occurred. In the present analysis, we have chosen two skiers for analysis: one skier who performed the movement in a controlled way, and another skier who lost balance, was forced into a hyperflexed knee joint position, and approximated the movement that is typically associated
with isolated ACL tears. We had hoped that differences in internal loading of the knee joint between these two skiers might help to identify why isolated ACL injuries occur. Interestingly enough, though, ACL forces were substantially smaller than PCL forces in both skiers and, furthermore, they occurred for a much shorter period of time than PCL forces. Maximal forces calculated in the ACL were 609 N (Figure 8), just at landing after the jump for Subject 1, and were well below failure loads of ACL (1,200–2,500 N; Hollis et al., 1988). Maximal PCL forces exceeded 3,000 N (Subject 2, Figure 9). Since PCL strength is about 60–100% higher than corresponding ACL strength (Kennedy, Hawkins, Willis, & Danylchuk, 1976), one may expect that failure loads of PCLs from young male subjects are about 4,000–5,000 N. Therefore, the maximal PCL loads calculated for Subject 2 are below the anticipated failure loads of this ligament.

The reason why ACL forces were small and only occurred at the beginning of the movement in Subject 1, and were virtually absent for Subject 2, except for one single instant in time, may be explained with the knee joint geometry. For this particular knee joint model, patellar tendon forces were parallel to the longitudinal axis of the tibia at a knee joint angle of 66° (Herzog & Read, 1993). For more extended knee joint angles, the tibia was pulled anteriorly relative to the femur by the patellar forces, thus tending to load the ACL; for more flexed knee joint angles, the patellar tendon tended to displace the tibia posteriorly relative to the femur, thus loading the PCL. Subjects 1 and 2 landed with their
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Figure 8 — Anterior and posterior cruciate ligament forces as a function of time for Subject 1.

Knee joints in a more extended position than 66°; thus quadriceps forces potentially helped to load the ACL. This actually happened in Subject 1. However, except for the very first few instants in time, knee joint angles were more flexed than 66° (Figure 1); thus the quadriceps forces observed for both subjects during most of the movement analyzed (Figure 7) tended to load the posterior cruciate ligament.

Therefore, from the present analysis, one may conclude that it is virtually impossible to tear the ACL during landing movements in a hyperflexed knee joint position, since the quadriceps forces would always protect the ACL and, if anything at all, may overload the PCL. This conclusion is further corroborated by studies investigating the effects of quadriceps force on ACL strain in human cadaveric specimens (Markolf, Gorek, Kabo, & Shapiro, 1990; Renstrom, Armur, Stanwick, Johnson, & Pope, 1986) and in male human subjects (Yasuda & Sasaki, 1987a, 1987b). Although somewhat different in magnitude, the general results of these studies indicated that quadriceps forces increase ACL strain toward knee extension and decrease ACL strain beyond about 45–60° of knee flexion.

In order to evaluate the model quantitatively, ACL forces calculated with our model were compared to the corresponding values obtained experimentally by Markolf et al. (1990) for a range of knee joint angles from full extension to 45° of flexion and a quadriceps force of 200 N (Table 1). ACL forces obtained theoretically and experimentally agreed well, and the tendency of decreasing
ACL loads with increasing knee flexion angles was clearly apparent in our theoretical calculations and the experimental values of Markolf et al. (1990).

There is an important difference between the loading conditions calculated for Subjects 1 and 2, and this difference may indicate how isolated ACL tears may occur when a skier loses control during the landing from a jump (e.g., Subject 2). Between $t = 0.137$ s and $t = 0.147$ s, Subject 2, who performed the landing movement in poor form, had a resultant moment at the knee joint in the flexor direction (Figure 3). This was unexpected, since the skier was fighting against being pushed into a hyperflexed knee joint position. When calculating internal forces for this period in time, one observes that quadriceps forces became zero (Figure 7) and posterior cruciate ligament forces became extremely large (Figure 9). According to the assumptions of the model, in particular Equation 6, the resultant knee flexor moment is produced by contraction of the hamstring muscles. However, it does not appear feasible that skiers would relax the quadriceps muscles and simultaneously contract the hamstring muscles while trying to gain balance in a situation where they are forced into a hyperflexed knee joint position.

For this reason, one may consider what the loading conditions would be at this particular period in time ($0.137-0.147$ s) if muscular forces were absent, that is, if the flexor moment was not produced by hamstring forces. Apparently,

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**Figure 9** — Anterior and posterior cruciate ligament forces as a function of time for Subject 2. Note that there is one instant in time ($t = 0.132$ s) where Subject 2 had forces in the ACL (60.6 N).
this scenario is reasonable, since it has been observed, through use of electromyo-
graphical techniques, that knee extensor and knee flexor muscles may become
electrically silent for periods of about 10–20 ms during landing conditions in
skiing similar to those observed for Subject 2 (P. Schaff, personal communication,
June 2, 1992). If muscular forces are zero, then resultant flexor moments may
have to be provided to a large extent by the ligaments of the knee joint. Since
moment arms of all four knee joint ligaments considered in this study are small
(Herzog & Read, 1993), corresponding forces would be high.

One way in which a loading situation as observed for Subject 2 during the
time period between 0.137 s and 0.147 s may arise is as follows: Quadriceps
forces in Subject 2 become extremely high at $t = 0.034$ s to $t = 0.0395$ s (Figure
7), in fact so high that they must be considered close to the maximal force that
may be produced by the subject, particularly considering that these forces were
required halfway down the race course, where the knee extensor muscles may
be expected to be fatigued. These high quadriceps forces may have caused a
reflex inhibition of the knee extensor muscles through Golgi tendon organ (GTO)
pathways. Such a reflex inhibition may influence muscular force production in
about 50 ms and, thus, appears feasible within the time frame shown in Figure

![Figure 10](image-url)
Figure 11 — Posterior cruciate ligament forces of Subject 2 as a function of time calculated using Equations 5 and 6 and simulating collateral ligament forces (Equation 4, \( v = 0.5 \), and Equation 3, \( k = 0 \), Simulation 1) and simulating hamstring activity (Equation 3, \( k = 0.2 \), and Equation 4, \( v = 0 \), Simulation 2).

However, a decrease of quadriceps force from over 9,000 N to zero within about 100 ms probably cannot be accomplished solely through GTO inhibition. Nevertheless, the idea that a bad landing that requires extremely high knee extensor forces causes a reflex inhibition of the knee extensor muscles appears feasible. Furthermore, as shown previously, such an inhibition of the knee extensor muscles coupled with a resultant flexor moment may produce large loads on the knee joint ligaments, particularly the ACL.

Forces in the hamstring muscles tend to load the PCL (Figure 11) and unload the ACL. Therefore, excessive forces in the ACL for the situation discussed in the previous paragraph might have been avoided if the relaxation of the quadriceps muscles had been accompanied by a simultaneous activation of the hamstring muscles. This idea had been rejected based on the mechanics of the movement, which requires the athlete to stay in control during the landing movement. It was also rejected based on unpublished findings that demonstrated silence in quadriceps and hamstring muscles in comparable situations. However, inhibition of knee extensor forces caused by afferent pathways from Golgi tendon organs could potentially activate hamstring muscles and so produce a "protection" effect for the ACL.

Calculating forces during highly dynamic movements, as attempted here,
Figure 12 — Bone-to-bone contact forces in the knee joint of Subject 2 as a function of time calculated using Equations 5 and 6 and simulating collateral ligament forces (Equation 4, \( v = 0.5 \), and Equation 3, \( k = 0 \), Simulation 1) and simulating hamstring activity (Equation 3, \( k = 0.2 \), and Equation 4, \( v = 0 \), Simulation 2).

Table 1

Comparison of ACL Forces

<table>
<thead>
<tr>
<th>Knee angles (°)</th>
<th>ACL forces (N) Experimental</th>
<th>ACL forces (N) Theoretical</th>
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<tr>
<td>0</td>
<td>73</td>
<td>78</td>
</tr>
<tr>
<td>5</td>
<td>56</td>
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<td>50</td>
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<td>14</td>
<td>24</td>
</tr>
</tbody>
</table>

Note. Table compares ACL forces obtained experimentally by Markolf et al. (1990) with ACL forces obtained theoretically using the model proposed in this study. The load applied to the quadriceps muscles was 200 N.
has limitations. First, the determination of the resultant knee joint forces and moments during the movement of interest relies on average data of mass, center of mass locations, and moments of inertia of limb segments obtained from the literature, and further relies on linear and angular accelerations of limb segments derived from displacement-time data of high-speed film. Second, calculations of internal forces require a knowledge of the precise geometry of the knee joint and, additionally, are based on assumptions of how force sharing among internal structures occurs. These limitations may appear sufficient to discourage anyone from attempting to calculate ligamentous forces in highly dynamic situations, particularly since it is not possible to perform a true validation of the theoretical predictions of internal forces at present. The research presented here was performed with an understanding of these limitations but also with the hope that technical developments in this area of research may allow a validation of our results in the future.

None of the skiers filmed during the training runs and the downhill race was injured. Furthermore, the two skiers that were analyzed in detail were selected specifically for their symmetrical landing on both skis and for their control of the skis, which were always pointing in the direction of movement. Obviously, an asymmetrical landing where forces were predominantly taken up by one ski would increase resultant knee extensor moments and thus internal loading of quadriceps muscles and possibly cruciate ligaments (Read & Herzog, 1992). Furthermore, loss of control over the skis may produce significant moments at the knee joint in internal or external rotation and so possibly contribute to ligament injuries in the knee joint (Shino et al., 1987). However, the aim of this study was to investigate possible mechanisms of isolated ACL tears that occur when a skier is forced into a hyperflexed knee joint configuration and tries to recover from that position. Therefore, rotational movements of the skis were not of interest, and a two-dimensional movement analysis approach could be used. In the future, a three-dimensional approach may be chosen to estimate internal forces for situations where skiers lose control over their skis or where landing movements are clearly asymmetrical.

References


**Acknowledgments**

This study was supported by an operating (W.H.) and a graduate student grant (L.R.) from NSERC of Canada.