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Impact and shock attenuation during landing activities from different heights on different surfaces

Yeon-Joo Yu

To the Graduate Council:

I am submitting herewith a thesis written by Yeon-Joo Yu entitled "Impact and shock attenuation during landing activities from different heights on different surfaces." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Human Performance and Sport Studies.

Songning Zhang, Major Professor

We have read this thesis and recommend its acceptance:

Wendell Liemohn, David R. Bassett

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Accepted for the Council:

Interim Vice Provost and
Dean of The Graduate School

Impact and shock attenuation during landing activities from different heights on different surfaces

A Thesis
Presented for the
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Degree
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Yeon-Joo Yu
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DEDICATION

I would like to dedicate this thesis to my parents Jin-Hae Yu and Han-Sook Kim and my brother Choul-Ho Yu. Their love and support have always encouraged and guided me through the better or worse times in my life.

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ABSTRACT

The purpose of this study was to examine impact shock attenuation during landing activities from different heights on different surfaces. Thirteen healthy and active subjects performed five trials of step-off landing from four different heights (30, 45, 60, and 75 cm) in shod and barefoot. Ground reaction forces (GRF), accelerations of the tibia and forehead, and kinematic data were sampled simultaneously. Increased heights caused increases in angular kinematic variables (range of motions, contact and maximum angular velocities of the ankle, knee, and hip joints). Few significant changes in kinematics were observed across the surface conditions. The first maximum GRF (F1) showed a trend of greater values in the shoe landing than that in the barefoot landing, with significant difference found at 75 cm. The second maximum GRF (F2) demonstrated a trend of greater values in the barefoot conditions than those in the shoe conditions. Greater F1 and F2 values were observed with increases in landing heights. The maximum head acceleration (AccHead) showed few significant changes in across the heights and surfaces. The first tibia acceleration (AccTibia1) was generally greater in the shoe conditions than that in the barefoot conditions. On the other hand, the second tibia acceleration (AccTibia2) displayed a trend of greater values in the barefoot conditions than that in the shod conditions, with significant difference found at 60 and 75 cm. The shock attenuation index (AtteIndex) in the barefoot conditions was significantly greater than that in the shoe conditions at all landing heights. The results suggested that the shoe provided an additional cushion to minimize impact forces and attenuate impact shock during the landing activities.

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Chapter I

Introduction

Jumping and landing are integral parts of many sport activities such as basketball, volleyball, and gymnastics. Many injuries of the lower extremity occur during the landing phase. According to a 1995 study by Kujala et al. [18], lower extremity injuries were most common in soccer, volleyball, and basketball athletes. With 54,186 sports injuries reported in Finland during a five-year investigation, the knee was reported as the most vulnerable joint. This result was in agreement with the studies of Arendat et al. [2] and Garrick [11]. Arendt et al. [2] found that knee injuries were the most prevalent injury in soccer and basketball using data obtained from the National College Athletic Association Injury Surveillance System. Garrick [11] examined 11,141 sports injuries in 1985, and reported that the knee joint was a commonly injured site. More than two thirds of injuries were due to overuse. In a study by Ferretti et al. [8], frequent knee injuries were often found in landing from a jump in volleyball players.

During landing, the human body experiences tremendous impact forces. Studies in biomechanics frequently focus on mechanisms and prevention of lower extremity injuries by investigating vertical ground reaction force (VGRF). Dufek and Bates [7] examined effects of heights, distances, and techniques on impact forces during landing. Increases in landing stiffness and landing heights were associated with increases of peak VGRF. These results were in agreement with Mizrahi et al. [25] who also found that greater VGRF was associated with greater landing heights. The first peak VGRF (F1) in toe-heel landing was significantly greater than in toe landings from the lower height. In addition, the toe-heel landing from the higher height produced greater ranges of motion for the hip, knee, and ankle joints than from the lower height.

Another aspect of biomechanical studies in dynamic activities is related to impact shock attenuation of the human body. Many studies have examined the shock attenuation capacity in walking and running. Only a few studies have addressed shock attenuation during landing activities, especially using information obtained from accelerometers. In a study conducted by Gross and Nelson [13], shock attenuation at the ankle was examined using two uniaxial accelerometers during barefoot landing from a vertical jump. No significant difference was found for peak calcaneal and tibial accelerations across the three surfaces (a midsole foam, a tartan rubber, and a cast aluminum). There was no significant difference between the peak calcaneal and tibial accelerations across all landing techniques (toe and toe-heel landing). The toe landing technique attenuated more peak VGRF and therefore was considered as a preferable landing technique for injury prevention.

Cavanagh et al. [3] examined VGRF during walking barefoot and in shoes. During barefoot walking, F1 was significantly greater and the time to F1 was shorter than the three footwear conditions. These results confirmed that differences of VGRF existed between the barefoot and shoe conditions. Wit et al. [38] examined GRF and kinematics during barefoot and shoe running. Nine long distance runners ran at three different velocities of 3.5, 4.5, and 5.5 m/s. The barefoot running produced significantly greater peak VGRF and loading rate, and shorter time to F1 than the shoe running. Barefoot running also showed greater plantarflexion and knee flexion compared to the shoe running.

Problem Statement

The purpose of the study was to investigate impact force and shock attenuation during landings on two different surface conditions and from different heights. Studies in biomechanics of landing have mainly focused on measuring impact forces during the landing using different experimental manipulations of landing techniques, heights, surfaces, and distances. However, very few studies have investigated shock attenuation using accelerometers in landing activities in shoe and barefoot conditions. By investigating the shock attenuation at the tibia and head using accelerometers while changing the surface and the height conditions, one could determine mechanisms of shock attenuation throughout the body during landing activities.

The results of this research may provide better understanding of performance enhancement, injury mechanisms, shock attenuation properties of shoes, and prevention of sport injuries during landing related activities.

Hypotheses

The following hypothesis were tested:

1) There are no differences in GRF during landings in barefoot and shoe conditions.
2) There are no differences in GRF during landings from different heights.
3) There are no differences in accelerations at the tibia and the head in the barefoot and shoe conditions.

4) There are no differences in accelerations at the tibia and the head from the different heights.
5) There are no differences in kinematic variables of the hip, knee, and ankle joints during landings in the barefoot and shoe conditions, as well as from the different heights.

Delimitations

The study was conducted within the following delimitations:

1) Thirteen active and healthy male subjects were selected from the student population at The University of Tennessee. They had no impairments of the lower extremities.
2) Eight test conditions included step-off landings with shoes from four different heights (30, 45, 60, and 75 cm) and step-off landings without shoes from the same four different heights.
3) Biomechanical signals were collected and analyzed for duration from 100 ms prior to the contact to the end of the landing phase for each trial.
4) Data were collected at 1200 Hz from a force platform (AMTI), two accelerometers (A353B17, Piezotronics Inc.), and at 60 Hz from a video camera (AG-188U, Panasonic) for each trial of the landing activity.

Limitations

The study was limited by the following factors:

1) Subjects were limited to the student population at The University of Tennessee.

2) Possible errors from placements of reflective markers.

3) Potential errors from the force platform, the accelerometers, and the video camera.

4) Possible errors due to the digitization of video.

5) The difference in the sampling frequency of the force platform (1200 Hz) and the video camera (60 Hz).

Assumptions

The following assumptions were made for this study:

1) Step-off landings could be modeled mechanically.

2) Biomechanical measurements used were sufficient for analyzing effects of step-off landings with different landing heights and surfaces.

3) Biomechanical instruments used were accurate.

4) All subjects were free of injuries of lower extremities at the time of testing.

5) The performance of the subjects was symmetrical, so therefore only the right side was assessed for the kinematics, GRF, and acceleration.

Chapter II

Literature Review

The purpose of this study was to investigate impact force and shock attenuation during landings on different surface conditions and from different heights. The intent of this literature review is to present research findings regarding biomechanics and impact attenuation during landing activities. Relevant research on walking, running, and pendulum experiments is also reviewed. The literature review is presented under these sub-titles: ground reaction force, acceleration, other relevant studies, and summary.

Ground Reaction Force

Gross et al. [13] investigated vertical ground reaction force (VGRF) during barefoot landing from a vertical jump. Eleven male recreational basketball players were divided into two groups according to two different landing styles: four subjects were involved in landings with toe; seven subjects were involved in landings with toe-heel. Three different surfaces (an aluminum force plate surface, a 9.0mm thick tartan rubber surface, and a 13.0mm thick midsole foam surface) were used to examine VGRF. The VGRF data were collected with a force platform (Kistler Type 9261A) at 1000 Hz. The magnitude of VGRF with the toe landing was reduced by 22%, compared with the toe-heel landing. The VGRF data showed no significant differences among the landing surfaces. The findings suggest that the toe landing was more favorable in impact attenuation and potentially in injury prevention.

Stacoff et al. [34] studied the effects of landing techniques on impact force in landings during volleyball blocks. The VGRF data were collected and sampled at 500 Hz using a force platform. The peak VGRF of toe landings ranged from 1000 to 2000 N. In toe-heel landings, the VGRF values ranged from 1000 to 6500 N. The kinematic results also showed that the degree of knee flexion was closely associated with the reduction of VGRF.

Ozguven et al. [29] evaluated impact forces during human landings. In the first experiment three gymnasts performed 10 typical landings starting from a hanging position on a horizontal bar (2.55m above the floor) onto a 2.5 x 3.0 m mat placed on a force platform (150 Hz). In the second experiment, two male and two female gymnasts were asked to land normally from a 0.45 m height onto the force platform. During both experiments, the subjects did not wear shoes. The VGRF values ranged from 8.2 to 11.7 BW (10.6 ± 1.1 BW) and 5.0 to 7.0 BW (5.9 ± 0.6 BW) in the first and second experiments, respectively.

Dufek and Bates [7] examined effects of height, distance, and technique on impact forces during landing. The mean peak VGRF (F1 and F2) and the mean time to F1 and F2 were used in analyses. Data were collected using a force platform (Type 9281-B, Kistler) and a high-speed film camera (Redlake Corporation). Three male subjects performed landings in test conditions with a combination of three landing distances (40, 70, and 100 cm), and three landing heights (40, 60, and 100 cm) using three landing techniques (stiff knee, slightly-flexed knee, and fully-flexed knee). The subjects performed three landing trials per condition for a total of 81 trials. Increases in landing stiffness and landing height were associated with increases of the peak VGRF.

These results were in agreement with Mizrahi et al. [25] who also found that greater VGRF was associated with greater landing heights. In their study, five subjects landed from two hanging positions on rings with arms either straight or flexed. Subjects performed both with toe-heel and toe only landings from the lower position (0.5 m above the floor), and toe landings from the higher position (1 m above the floor). The peak VGRF (F1 and F2) and the range of motion for the hip, knee, and ankle joints were examined. The F1 magnitude in toe-heel landings was significantly greater than in toe landings from the lower height. In addition, the toe-heel landings from the higher height produced greater ranges of motion for the hip, knee, and ankle joints than the toe-heel landings from the lower height.

Panzer et al. [30] examined VGRF acting on six elite gymnasts during single back somersaults (SBS) and double back somersaults (DBS). The VGRF data were collected with two Kistler force platforms and sampled at 500 Hz. To obtain kinematic data, five reflective markers (gleno-humeral joint, greater trochanter, femoral condyle, lateral malleolus, and fifth metatarsal-phalangeal joint) were placed along the side of subjects and performances were recorded with a high-speed film camera. The values of peak VGRF for DBS ranged from 8.8 to 14.4 BW for single-leg landings; the peak VGRF in DBS was 6.7 BW higher than in SBS.

Ricard and Veatch [31] investigated impact forces of two aerobic dance movements: the low impact front knee lift (LFKL) and the high impact front knee lift (HFKL). The variables included peak impact force, time to peak impact force, and peak loading rate. The mean peak impact force was 0.98 and 1.98 BW for LFKL and HFKL, respectively. The time to peak impact force in LFKL was significantly longer than in

HFKL. The mean peak-loading rate was 42.55 and 14.38 BW/s for HFKL and LFKL, respectively. Based on these results, it can be observed that LFKL produced significantly lower impact forces than HFKL.

Acceleration

Landing

In a study conducted by Gross and Nelson [13], shock attenuation at the ankle was examined during barefoot landing from a vertical jump. The experiment conditions included landing from vertical jumps with two landing techniques (toe and toe-heel) onto three different landing surfaces (a midsole foam, a tartan rubber, and a cast aluminum). Two uniaxial accelerometers (Endevco 2222B.) were used to measure accelerations at the tibia and the calcaneus. In pilot data, damping factors of 0.239 and 0.552 were determined for the calcaneus and the tibia, respectively. These values showed that the acceleration measurement at the tibia was more attenuated than at the calcaneus. The average of peak accelerations at the calcaneus and tibia across the three surfaces were 20.8 and 14.3 g, respectively. However, no significant difference was found between the peak calcaneal and tibial accelertions across the three surfaces. There was also no significant difference between the peak calcaneal and tibial accelerations between the two landing techniques.

Walking

In the study performed by Voloshin et al. [37], the ability of shock absorption was investigated among healthy subjects and subjects with degenerative changes in bones and/or joints. The data were collected using accelerometers (Type 4371, Bruel and Kjaer) attached to the tibial tuberosity and forehead of each subject during walking at speed of 4.2 km/hr. Shock absorption capacity, K, was calculated with the following formula:

$$K = \frac{\text{Amplitude on tibial tuberosity}}{\text{Amplitude on forehead}}$$

The healthy subjects had significantly higher K values than the patients. The higher K value indicated greater shock attenuation capacity in the healthy subject group. This result confirmed that the lower values of the shock-absorbing capacity of the human locomotor system were related to degenerative changes in bones and/or joints.

Wosk and Voloshin [39] examined the shock attenuation between the forehead and tibial tuberosity in 39 healthy subjects. Miniature accelerometers (Type 4371, Bruel & Kjaer) were mounted on the forehead and the tibial tuberosity of the subjects. The subjects performed walking without shoes at speed of 4.0km/hr. Twenty-three subjects showed approximately symmetrical value of the peak-to-peak acceleration in the first cycle (PP1). Sixteen subjects showed asymmetrical values of PP1, whereas a symmetrical value was considered as 10 % or less in difference of PP1 values between the right and left heel strikes. Using the same formula [37], K was used for evaluating the shock attenuation between the knee and the forehead. The asymmetrical subjects showed a 25% lower K ratio than the symmetrical subjects, implying a lack of shock absorbing capacity of the hip-knee-joint system. Even though all subjects were healthy and reported no orthopedic diseases, the authors suggested the development of degenerative joint diseases in the asymmetrical subjects.

Running

Shorten and Winslow [33] examined impact shock attenuation during treadmill running. Twelve healthy subjects performed running at different speeds (2 to 5 m/s). A piezo-resistive accelerometer (EGA-125-250D) was mounted on the skin of the medial-anterior aspect of the tibia to measure shock of the tibia. In order to measure shock of the head, an accelerometer attached to a bite-bar was affixed to the teeth of the subjects. As the treadmill speed increased, the amplitude and frequency of the leg acceleration increased. However, the peak head acceleration did not show any significant changes due to the increase of the treadmill speed. At higher frequencies (above 6 Hz), the acceleration of the head showed no significant peak power. The results suggested that the body served as a low-pass filter, attenuating the impact shock of higher frequencies.

Hamill et al. [15] examined the relationship between stride frequencies and shock attenuation during treadmill running. Two accelerometers (PCB Piezotronics) were mounted on the antero-medial distal aspect of the left tibia and the frontal bone of the head. Ten healthy male subjects ran at –20%, -10%, 0 %, +10%, and +20% of a preferred stride frequency at a preferred running speed. A power spectral analysis displayed two peaks of power for the leg acceleration. One was at 5 to 7 Hz and the other at 10 to 15 Hz, respectively. A single peak for the head acceleration was found below 10 Hz. The head acceleration was constant across the stride frequency conditions. The powers and frequencies at which the peaks occurred for the leg and the head were similar to the findings of Shorten and Winslow [33].

Lafortune and Hennig [19] examined accelerations obtained from a bone-mounted accelerometer during walking and running. A bone-pin was inserted into the proximal end of the right tibia with a triaxial accelerometer. Six subjects performed 5 trials of running at 4.5 m/s, and three components of accelerations and ground reaction forces were collected at 1000 Hz. One of the subjects performed three trials of walking. The acceleration signal was analyzed using a power spectrum analysis. The average values of peak tibial axial acceleration (At) were 3.1 and 5.3 g for walking and running, respectively, whereas the average peak tibial axial acceleration (Ai) estimated from ground reaction forces were 2.6 and 10.3 g for walking and running, respectively. No significant differences were observed in times to At and Ai during between walking and running.

Pendulum Experiment

Lafortune et al. [21, 22] conducted two studies using a pendulum device. The first study [21] examined relationships among GRF, impact shock, knee joint angles, and different surfaces in the pendulum experiment. The pendulum device was composed of a lightweight bed and a Kistler force platform (Model #9281B11) mounted on a wall. All subjects laid supine with the right leg extended and the left leg flexed on the bed. The subjects positioned the right leg so that it barely touched the force platform. A uniaxial accelerometer (EGA-100D, Entran) was mounted on the antero-medial of the shank 15 cm proximal to the medial malleolus. The velocity at the time of impact with the force platform was set to 1.0 m/s. Nine different test conditions were conducted with combinations of three initial knee angles (IKA) of 0, 20, and 40 degrees and three surfaces of barefoot, soft (a 2.5 cm thick layers of EVA form with Asker C of 40), and hard (a 2.5 cm thick layers of EVA form with Asker C of 60) contact materials. The variables included peak impact force, time to the peak impact force, peak acceleration, and time to the peak acceleration. The results demonstrated that larger IKA were associated with reduction of initial peak impact force, and larger IKA increased peak shank acceleration on the three different surfaces. The soft surface caused reduction of peak shank acceleration at the three IKA. Increases in IKA were associated with shorter times to the peak impact force and the peak shank acceleration except at the barefoot condition with the 0 and 40 ° IKA. The soft surface produced longer times to the peak impact force and the peak shank acceleration at the all three IKAs.

In the second study [22], the authors focused on shock transmission of the body using the same pendulum impact device. Test conditions included combinations of three different impact velocities of 0.9, 1.05, and 1.20 m/s, and two different surfaces of soft (2.5 cm thick layers of 40 Asker C) and hard (2.5 cm thick layers of 60 Asker C) materials. Two biaxial accelerometers were mounted on the head and the shank to obtain impact shock of the seventeen male subjects. Right knee angle was kept 20 ° flexion during the impact. Peaks and times to peaks of head and shank accelerations were obtained. The peak shock transmission of the body was calculated as a ratio of the head and shank peaks. In addition, the time to the shock transmission was calculated from interval between the head peak and shank peak acceleration. With increases in the impact velocity, the peak shock and the time to the peak shock were increased in magnitude and decreased in time for both head and shank accelerations. The hard surface was linked to greater peak shock and shorter times to peak shock for the head and the shank. Significant differences in the body shock transmissions were found among the three different velocities; there was a significant difference in the body shock transmissions between the soft and the hard surfaces. The soft surface introduced greater shock transmission than the hard surface.

Other relevant studies

Landing

In the study conducted by Dufek et al. [6], two peaks of VGRF (F1 and F2) were examined in four different shoe conditions: two basketball shoes (C1and C2), a running shoe (C3), and a volleyball shoe (C4). Five male subjects landed from a 60-cm height onto a force platform (1000Hz). Four variables were obtained from the GRF data, including forefoot impact force (F1), rearfoot impact force (F2), time to the occurrence of F1 (T1), and time to the occurrence of F2 (T2). The average values for F1 and F2 were 1.21 and 3.00 BW, respectively. The average T1 and T2 were 14.8 and 56.5 ms, respectively. The first basketball shoe (C1) produced statistically lower values as well as shorter time of both F1 and F2 than the second basketball shoe (C2). Comparing shoe conditions across the subjects, C1 caused less values of F1 for all subjects.

Gross and Bunch [12] investigated VGRF in the thickness of the different midsole materials during landings from a jump. Three midsole materials were used: a 2 mm thick rigid paperboard as a stiff spring (STS), polyurethane as a subordinate spring/dominant damper (SS/DD), and ethyl vinyl acetate as a dominant spring/subordinate damper

(DS/SD). The three midsole materials were inserted into basketball shoes. Nine male subjects performed five vertical jumps in each of the three different midsole conditions. A kistler force plate (Type SN 9807, 333 Hz) was used to measure VGRF. The peak VGRF did not show any significant difference among the midsole materials.

Fukoda [10] analyzed muscle power and joint kinematics in landings on surfaces of different stiffness. Four male subjects landed from a 0.2 m height onto surfaces of two different stiffnesses (K1; 49.0 kN/m, K2; 392.0 kN/m). The peak power at the knee joint during landing on K2 was significantly larger than when landing on K1. There was no significant difference for the peak power at the ankle between two surfaces. The results suggested that increases in surface hardness produced increases in the impact load on the knee extensors.

Walking

Cavanagh et al. [3] examined VGRF and kinematic data during walking barefoot and in shoes. Ten male subjects (Mean body weight = 693.3 N) performed five trials of walking at a speed of 1.32 m/s in barefoot and three shoe conditions (army boots, leather street shoes, and crepe soled casual shoes). Force platform (1580 Hz) and a high-speed kinematic data (200 Hz) were collected for three trials for each subject. During the barefoot walking, F1 was significantly greater and the time to F1 was shorter than the three footwear conditions. During the barefoot walking, the ankle was significantly more dorsiflexed than shoe walking during the swing phase. However, there was no significant difference in the posture at contact between the conditions. Only the knee was fully flexed at contact during the barefoot walking. These results confirmed that differences in VGRF exist between barefoot and shoe walking.

Lafortune et al. [20] studied VGRF and acceleration in walking in different types of footwear. A 6-g triaxial Entran piezoresistive accelerometer was inserted into the proximal right tibia of five subjects using a bone pin. Both VGRF (9281 Kistler) and tibial acceleration data were sampled at 1000 Hz. The subjects performed three trials of walking at 1.5 m/s in three footwear conditions (barefoot, leather-soled street shoe, and athletic shoe). The variables examined included initial peak ground reaction force (IPF), initial peak tibial acceleration (IPA), force loading rate (FLR), and acceleration transient rate (ATR). FLR and ATR was calculated with the following formulas:

$FLR = 0.7\ IPF/\Delta t_F$, where Δt_F are the time from 0.2 IPF to 0.9 IPF.

$ATR = 0.7\ IPA/\Delta t_A$, where Δt_A are the time from 0.2 IPA to 0.9 IPA.

The barefoot condition produced higher IPF and faster FLR than the shoe conditions ($p<0.05$). Significant differences ($p<0.05$) were also found for IPA and ATR among all three footwear conditions. The barefoot condition produced higher IPA and ATR than the street shoes, and the street shoes produced higher IPA and ATR than the athletic shoes. Difference in IPF and FLR between walking barefoot and in shoes implied that the shoes were responsible for the reduction of the impact force and loading rate. The lower values of IPA and ATR in athletic shoes explained that both heel fat pad and compliant soles were involved in cushioning of the impact shock.

Fredrick et al. [9] determined effects of shoe design parameters on impact loads. These parameters included hardness of midsole materials, heel height, and angle of midsole flare. They found that shoe design parameters played a role in shock attenuation reflected in kinematic and kinetic data. This observation indicated that shoes could either prevent injuries or cause injuries.

A study conducted by Denoth and Nigg [5] examined the difference of the partial load on the ankle and knee joint using different surfaces during walking and running. A partial load on the ankle and knee joint was defined as the mechanical load of the ankle and knee joint. The partial loads of the ankle and knee was calculated with the following formulas:

$$f_{foot} = m^* \cdot v_0 \cdot \sqrt{\frac{f_{floor} \cdot f_{heel}}{m^* \cdot (f_{floor} + f_{heel})}}$$

$$f_{knee} = (m^* - m_{tibia}) \cdot v_0 \cdot \sqrt{\frac{f_{floor} \cdot f_{heel}}{m^* \cdot (f_{floor} + f_{heel})}}$$

where, v_0 = velocity of the effective mass (m^*) before impact (vertical)

f_{floor}, f_{heel} = spring constant of floor and heel

The partial loads of both knee and ankle joint were greater on synthetic floors than on grass. It was observed that knee and ankle joints were vulnerable to injury on synthetic floors. This study showed the importance of playing surface in sports events such as jumping, walking and running.

Running

Wit et al. [38] examined spatio-temporal variables of GRF and kinematics during barefoot and shoe running. Nine long distance runners (body mass: 70±9 kg; shoe size: UK 8.9 ± 1.5) ran at velocities of 3.5, 4.5, and 5.5 m/s. Among nine subjects, seven subjects performed additional barefoot running at 4.5 m/s. The three components of GRF and foot movement data were collected using a Kistler force platform and two high-speed video cameras. The GRF data were obtained from 10 trials and the kinematic data were analyzed from 5 trials of running. The barefoot running produced significantly greater loading rate and shorter time to F1 than the shoe running. The barefoot running also showed greater plantarflexion and knee flexion, compared to the shoe running.

During the examination of the human heel pad, De Clercq et al. [4] found that there were differences in peak VGRF in barefoot and shoe running. In barefoot running, the F1 and the loading rate of F1 were higher than the shoe running. In addition, the time to F1 was shorter in the barefoot running compared to the shoe running.

Nigg et al. [27] investigated effects of midsole hardness and running velocities on VGRF during toe-heel running. Three pairs of shoes (size 9) were provided to fourteen subjects. The midsole was altered to 25, 35, and 45 shore for soft, normal and hard hardness. Subjects were asked to run at velocities of 3, 4, 5, and 6 m/s (±0.2 m/s). Variables included peak impact force, time to peak impact force, and peak active force. In order to obtain these variables, a force platform (1020 Hz) and a high-speed camera (200 Hz) were used. Increases in running velocities caused an increase in the peak impact force and a decrease in the time to peak impact force. As the velocity increased from 3 m/s to 6 m/s, the peak active force increased from 1.86 kN to 2.26 kN. Increases in midsole hardness slightly decreased the peak impact force. However, it was not statistically significant. The time to peak impact force was significantly decreased as the midsole hardness increased from soft to normal.

Nigg and Liu [26] examined effects of soft and hard midsole during running. The mean peak VGRF was 1339 N and 1187 N for the hard and the soft shoe. The hard midsole shoe produced significantly higher VGRF than the soft midsole shoe. This result was in an agreement with another study by Nigg et al. in 1981 [28]. Nigg and his colleagues [28] reported that soft sole shoes produced lower VGRF than hard sole shoes during 5 m/s running. Furthermore, the peak VGRF was higher in a spike shoe than in a soft midsole training shoe during a vertical jump.

Valiant et al. [36] examined the acceleration at the tibia during barefoot and shoe running. An accelerometer was mounted on the anteromedial distal tibia; four subjects ran five trials in each condition. In the shoe condition, the peak acceleration and the time to the peak acceleration were 6.1 g (± 2.5 g) and 8.3 ms (± 1.8 ms), respectively.. The peak acceleration and the time to the peak acceleration were 7.2 g (± 2.5 g) and 6.0 ms (±1.6 ms) for the barefoot condition. Only the time to the peak acceleration for the barefoot condition demonstrated a significantly lower value.

Summary

This chapter illustrates biomechanics and impact attenuation during landing and other activities. The emphasis in the literature was placed on evaluating VGRF and acceleration during walking, running and landing. However, research addressing shock attenuation on different surfaces during landing activities is quite limited. Further investigations of shock attenuation on different surface conditions and from different heights during landing activities are warranted.

Chapter III

Research Methods

Experimental Methods

Experiments were conducted to investigate attenuation of impact force and shock during landing from different heights on different surfaces. The protocol for the experiment consisted of a warm-up, anthropometric measurements, and eight test conditions. Five trials of step-off landings in each of eight different conditions, for a total of 40 trials, were performed by each subject.

Subjects

All subjects signed an informed consent form approved by the Institutional Review Board at The University of Tennessee (Appendix G) prior to their participation in the study. Subjects were recruited from the student population at The University of Tennessee. Thirteen healthy and physically active male subjects volunteered to participate in the study. A healthy and physically active male subject was defined for this study as one who had no history of impairments to his lower extremities and who participated in recreational sports 2-3 times a week. All subjects were briefed on the purpose, procedures, risks, and benefits of this study before their participation. Subject information is provided in Appendix B.

Instrumentation

All testing was conducted in the Biomechanics/Sports Medicine Lab, Room 135, HPER Building at The University of Tennessee. The biomechanical instrument used in this study included a force platform (OR6-7, AMTI), two accelerometers (A353B17, Piezotronics Inc.), a video camera (AG-188U, Panasonic), lab shoes, a trigger device, a reference frame, reflective markers, an analog/digital (A/D) converter, and an Ariel Performance Analysis System (APAS, Ariel Dynamics, Inc.) for data collection and processing.

Kinematics

A video camera (AG-188U, Panasonic) was used to obtain kinematic data from the right sagittal view of the subjects during the test. The camera (60 Hz) was set parallel to the floor and the shutter speed was set at 1/1000 sec. A reference frame (width= 140.97 cm, length= 186.69 cm) was used to obtain scale factors in order to convert anatomical coordinates of the reflective markers. The reference frame has four coplanar reflective markers placed on the four corners of the structure.

Reflective markers were placed on the right side of the body at the shoulder, hip, knee, ankle, heel, and the head of the fifth metatarsal (Figure 1). Using the Ariel system, the recorded video images were digitized to obtain coordinates of these markers throughout during the activity. The digitized coordinates were then imported into a customized program to determine the time-history and discrete events of linear and angular positions, velocities, and accelerations.

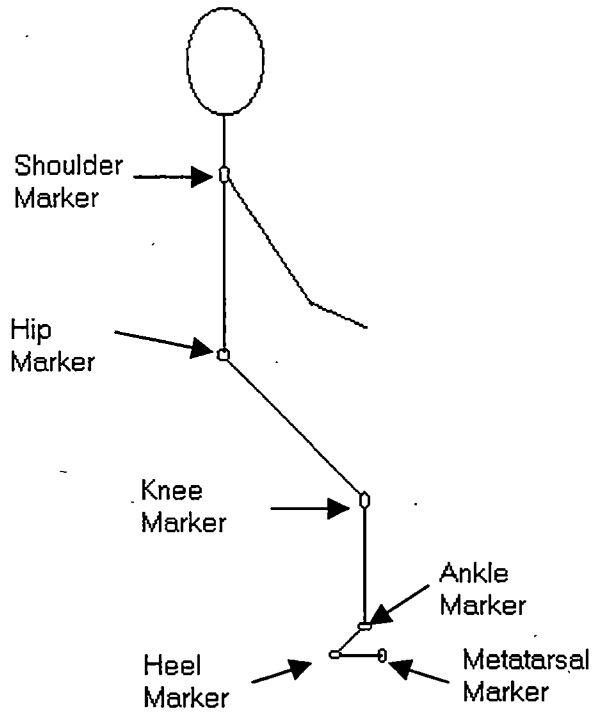


Figure1. Placement of reflective markers

Force Platform

A force platform (OR6-7, AMTI) flush with the surrounding floor was used to measure ground reaction forces (GRF) and moments during the test. The GRF data included Fx, Fy, and Fz, representing medial-lateral, anterior-posterior and vertical forces respectively. Mx, My, and Mz represented moments applied about Fx, Fy, and Fz axes. Signals from the force platform were sampled for 1.5 sec at a frequency of 1200 Hz and amplified before being stored in the APAS computer through the A/D converter.

Accelerometer

Two miniature accelerometers (A353B17, Piezotronics, Inc.) were used to measure accelerations at the forehead and distal tibia of the subjects. Signals from the accelerometers were also sampled at a frequency of 1200 Hz using the APAS. The accelerometer has a range of 500 g and a resolution of 0.005g. Two accelerometers were securely fastened to the tolerance of the subject, on the forehead and the anteromedial surface of distal tibia of the subject with adhesive tape and Velcro straps.

Synchronization

The force platform, the accelerometers, and the sagittal view video were simultaneously recorded during the experiment. The synchronization between the kinematic and analog signals (the force platform and the accelerometers) was achieved by using a customized trigger device with a light emitting diode (LED).

Shoe

Subjects wore lab shoes (Noveto, Adidas) provided by the Biomechanics/Sports Medicine Lab. The midsole and outsole of the shoe consisted of lightstrike EVA and minimal carbon rubber. The diagram of experimental setup is shown in Figure 2.

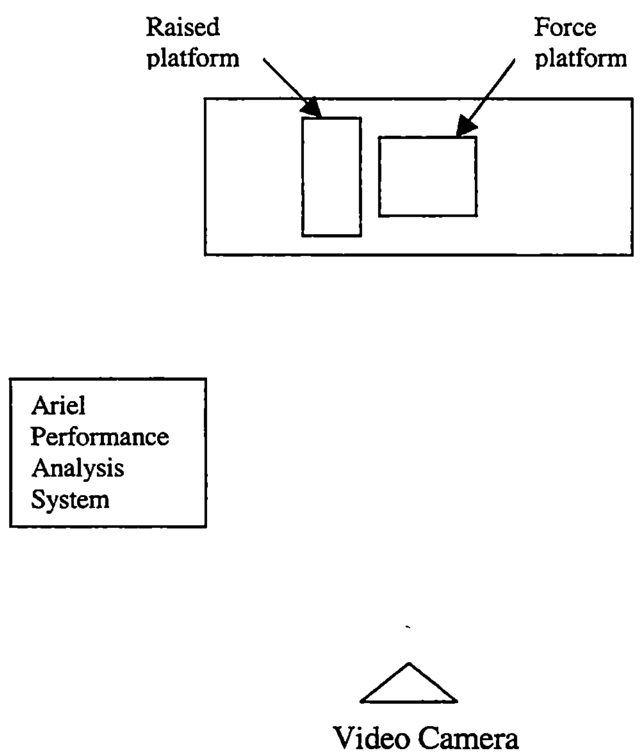


Figure 2. Diagram of experimental setup

Experimental Protocol

Prior to their participation in this study, subjects were briefed on the purpose and the procedures of the study by the principal investigator. On the test day, the subjects were further informed about the purpose, the number of conditions, the number of repetitions, and performance requirements of the study. The test session took approximately 1.0 hour including practice and familiarity with the testing protocol. Forty trials of step-off landing were performed by the subjects in eight conditions. The eight test conditions included landings with and without shoes from four different heights: 30, 45, 60 and 75 cm.

A pilot study was conducted to determine the appropriate highest height for the barefoot landing. Two subjects performed landings from four different heights (30, 45, 60 and 75 cm) with and without shoes. They were able to land from the 75 cm height in barefoot without changing their landing techniques. The subjects did not show significant changes either in range of motion (ROM) of lower extremity joints or in peak VGRF at the different landing heights across the two surface conditions. The subjects reported the 75 cm landing was within their tolerance. Therefore, the 75 cm was chosen as the highest height for the experiment.

The subject began the test session with a warm-up by riding a stationary bike for five minutes. The retro-reflective markers were placed on the acromioclavicular joint, the greater trochanter, the tibial epicondyle, the lateral malleolus, the heel, and the head of the fifth metatarsal. In the shoe conditions, the last two markers were affixed to the corresponding sites on the lateral side of the shoe. These markers were used to obtain right sagittal kinematics of the subjects during the landing activities.

Anthropometric measurements were obtained before the actual testing. The proximal and distal circumferences and length of lower extremity segments were measured three times (Table 1); the mean value of these measurements was used in the subsequent analyses. The anthropometric measurements were used to estimate inertia characteristics and center of gravity (COG) of each lower extremity segment, and the location of COG of the total body using a mathematical model [16].

Table 1. Anthropometric measurement and definitions

Anthropometric Measurement
FDC = Foot Distal Circumference
FPH = Height of lateral malleolus
FL = Foot Length
LDC = Leg Distal Circumference
LPC = Leg Proximal Circumference
LL = Leg Length
TDC = Thigh Distal Circumference
TPC = Thigh Proximal Circumference
TL = Thigh Length
AMA = Ankle Moment Arm
Measurement Definition
FDC = Circumferential measurement from the head of first metatarsal to the fifth metatarsal
FPH = Height measurement from floor to center of the lateral malleolus
FL = Length measurement from the lateral malleolus to the head of the fifth metatarsal marker
LDC = Circumferential measurement of the ankle superior to the mallelus
LPC = Circumferential measurement of widest girth of the leg
LL = Length measurement from the ankle to the tibial epicondyle marker
TDC = Circumferential measurement of the femur just superior to the femoral epicondyle
TPC = Circumferential measurement of the widest girth of the thigh
TL = Length measurement from the tibial epicondyle marker to the hip marker
AMA = Length measurement from center of the heel marker to midline of the Achille's tendon

Prior to the experiment, the body weight was measured on the force platform. During the test, the subject was instructed to land with the right foot on the force platform with the left foot on the adjacent floor in a symmetrical manner. The subject performed five step-off landings in each of the eight conditions. The order of the surface conditions was randomized for each height and the height was changed from low (30 cm) to high (75 cm) height.

Data Processing

The data processing procedure was divided into two categories: kinematic and kinetic data.

Kinematic Data

Images collected from the video camera were used to obtain kinematic variables. The data were processed in four steps: capturing, digitizing, decoding/smoothing, and computing. First, a total of 60 frames of video images was captured and stored for each trial on the APAS, with 10 frames prior to and 50 frames following the foot contact with the force platform. Second, the reflective markers were digitized using the APAS. The reference frame was also digitized to obtain scale factors to convert the coordinates of digitized reflective markers from a screen reference system to a lab reference system. The third step involved decoding, smoothing and reconstructing the digitized coordinates using a customized computer program written in Microsoft Visual Basic 6.0. The digitized coordinates were smoothed using an algorithm to obtain optimal cutoff frequencies individually for x and y coordinates of each reflective marker [17]. A

Shannon algorithm was used to reconstruct the video signal from 60 Hz to 240 Hz [14]. In the fourth step, the decoded time-history file was imported into the second customized program to compute linear and angular kinematic variables and determine corresponding discrete events. These variables included contact position/velocity, maximum and time to maximum position/velocity, and minimum and time to minimum position/velocity for the hip, knee, and ankle joints.

Kinetic Data

Data collected from the force platform and the accelerometers were analyzed in two steps. Analog data file stored on the APAS file was decoded using another Visual Basic program to obtain ASCII time-history of GRF and acceleration data. Second, using the fourth Visual Basic program, the decoded data files were imported to compute and obtain GRF and acceleration variables. These variables included the first (F1) and second (F2) maximum and vertical GRF and the times (T1 and T2) at which they occurred as well as the first and second maximum acceleration values for the head and the tibia and the times at which they occurred.

Statistical Analysis

Descriptive statistics (means and standard deviations) were calculated for each kinematic and kinetic variable. A two-way (surface × height, 2×4) analysis of variance (ANOVA) was employed for selected variables with using a statistical package SAS (SAS Institute, Inc., Cary, NC, USA). Post-hoc comparisons were performed using slicing interactions in SAS [32]. The significance level was set at $p < 0.05$.

Chapter IV

Results

The purpose of this study was to investigate the shock and impact attenuation during landing activities from different height on different surfaces. The results of the kinematic and kinetic data were obtained for eight different conditions: C1 - 30 cm with shoe, C2 - 45 cm with shoe, C3 - 60 cm with shoe, C4 - 75 cm with shoe, C5 - 30 cm without shoe, C6 - 45 cm without shoe, C7 - 60 cm without shoe, and C8 - 75 cm without shoe. Kinematic and kinetic data were collected and analyzed for thirteen male subjects. Among the thirteen subjects, ten subjects landed with a toe-heel landing technique (Group 1) and three subjects landed with a flatfoot landing technique (Group 2) during the experiment. The individual subject results of kinematics, VGRF, and acceleration are provided in Appendix C, D, and E. The following sections mainly focus on the kinematic and kinetic data for Group 1.

Kinematics

Kinematic variables included the followings of the ankle, knee, and hip joint: contact angle (Cont), maximum angle (Max) and minimum angle (Min), time to Max (Tmax) and Min (Tmin), range of motion (ROM), contact velocity (ContVel), maximum velocity (MaxVel), and time to maximum velocity (TmaxVel). The contact angle is indicative of the joint position at the moment the foot contacts the ground. The maximum joint angle reflects the greatest angle of the joint during the landing phase.

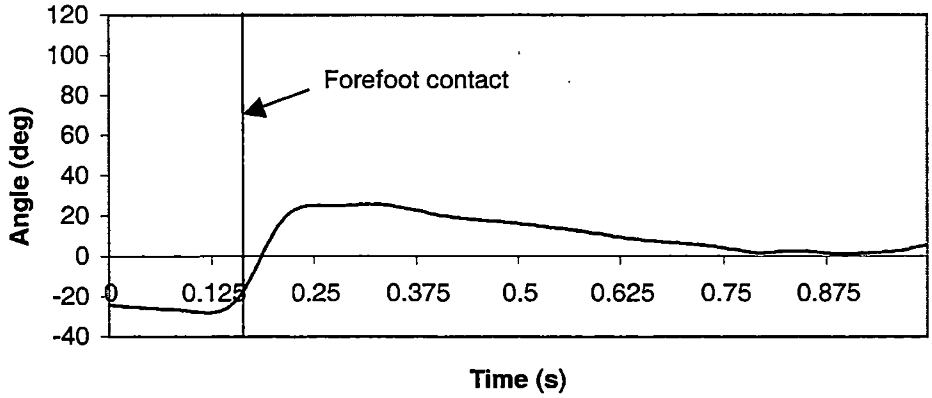
The minimum joint angle reflects the smallest angle during the landing phase. The time to the maximum and minimum joint angle represents how long it takes to reach the maximum and minimum angle. The range of motion is defined as the difference between the maximum and minimum angles during the landing phase. The contact velocity reflects the velocity at the moment the foot contacts the ground. The maximum velocity represents the highest velocity achieved during the landing phase. The time to maximum velocity reflects the time associated with the maximum velocity.

Ankle Joint

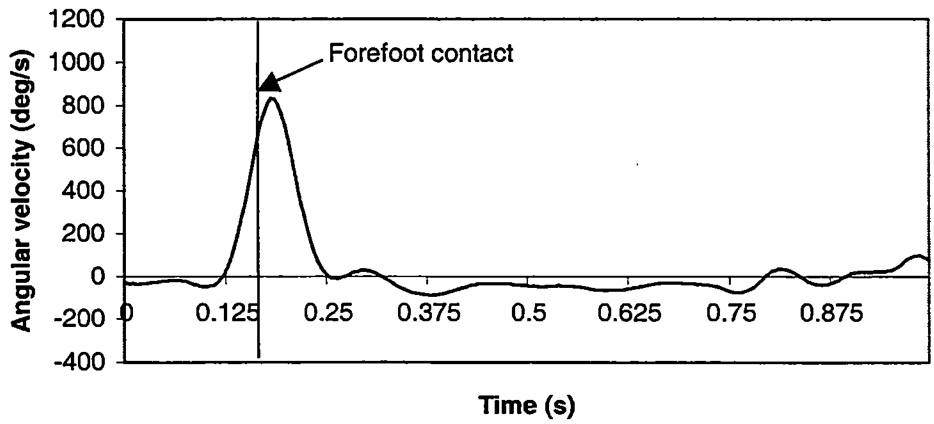
Representative curves of the ankle joint angle and angular velocity are provided in Figure 3. Representative curves of the ankle joint for barefoot at 60 cm are provided in Appendix F. The ankle joint angle was changed from a negative angle at the contact to a positive angle afterwards. A positive angle indicates dorsiflexion and a negative angle indicates plantar flexion. A minimum angle was associated with forefoot contact. A positive ankle angular velocity is associated with dorsiflexion while a negative velocity is associated with plantarflexion.

Group 1

The two-way ANOVA showed a significant omnibus F for ankle angular ContVel ($F = 3.47$, $p<0.05$) and MaxVel ($F = 8.67$, $p<0.05$). A significant main effect of height was found for the ankle angular ContVel and MaxVel. No significant surface main effect and interactions (surface × height) were found for these variables. No significant differences were found for the ankle Cont, Max, Min, Tmax, Tmin, ROM, and TmaxVel.



(a) Joint angle



(b) Joint angular velocity

Figure 3. Representative ankle joint curves for shoe at 60 cm (Group 1).

The post-hoc comparison showed that the ContVel at 60 and 75 cm with shoe and barefoot conditions produced significantly higher than the ContVel at 30 cm (Table 2). The post-hoc comparison for the ankle angular MaxVel in the shoe conditions revealed significant differences between 30 and 60 cm, between 30 and 75cm, between 45 and 60 cm, and between 45 and 75 cm. The ankle angular MaxVel in the shoe conditions at the lower height was smaller than that at the higher height. The ankle angular maximum velocities at 60 and 75 cm with barefoot were significantly greater than that at 30 cm.

Group 2

The two-way ANOVA showed significant omnibus F for the ankle joint ROM ($F = 4.71$, $p<0.05$), ContVel ($F = 17.92$, $p<0.05$), MaxVel ($F = 16.47$, $p<0.05$), and TmaxVel ($F = 4.90$, $p<0.05$). Significant main of height and surface effects was found for the ankle joint ROM, ContVel, MaxVel, and TmaxVel. No interactions were found for those variables.

The post-hoc comparison for ROM revealed significant differences between 30 and 75 cm in both shoe and barefoot conditions (Table 3). At the heights of 45 and 60 cm, the ankle joint ROM with barefoot were significantly greater than those at the same height with shoes.

Table 2. Means and standard deviations of ankle joint kinematic variables (Group 1).

Surface	Height	Cont	Max	Tmax	Min	Tmin	ROM	ContVel	MaxVel	TmaxVel
Shoe	1	-14.897	22.779	0.229	-15.580	0.038	38.359	470.028	683.756	0.017
		(11.255)	(6.900)	(0.091)	(10.476)	(0.095)	(8.854)	(116.647)	(174.354)	(0.006)
	2	-16.348	25.396	0.211	-16.359	0.012	41.755	634.729	835.153	0.015
		(10.058)	(7.679)	(0.059)	(10.050)	(0.038)	(7.678)	(71.833)	(118.392)	(0.005)
	3	-18.567	25.211	0.213	-18.718	0.024	43.929	684.497 [b]	985.048 [b,d]	0.015
		(10.721)	(8.311)	(0.055)	(10.356)	(0.076)	(7.882)	(163.268)	(132.952)	(0.007)
	4	-17.241	25.731	0.205	-17.503	0.031	43.235	813.144 [c,e]	1083.614 [c,e]	0.013
		(10.359)	(9.257)	(0.058)	(10.015)	(0.068)	(5.733)	(143.039)	(160.296)	(0.004)
Barefoot	1	-20.748	21.387	0.211	-21.296	0.035	42.684	494.517	738.705	0.020
		(10.252)	(6.226)	(0.084)	(9.637)	(0.056)	(7.927)	(70.479)	(90.671)	(0.007)
	2	-21.694	22.047	0.214	-21.694	0.000	43.741	558.961	856.479	0.020
		(8.576)	(6.896)	(0.083)	(8.576)	(0.000)	(7.434)	(98.373)	(94.936)	(0.006)
	3	-19.586	22.939	0.212	-19.602	0.012	42.541	694.116 [b]	952.677 [b]	0.016
		(8.825)	(7.904)	(0.076)	(8.817)	(0.037)	(5.831)	(138.759)	(83.654)	(0.006)
	4	-20.589	22.826	0.215	-20.976	0.035	43.802	688.142 [c]	991.694 [c]	0.017
		(8.055)	(7.710)	(0.057)	(7.729)	(0.079)	(5.479)	(83.651)	(90.597)	(0.005)

Note: Angle and ROM units are in degrees and units of time are in s.
Velocity units are in deg/s.
Standard deviation values are in parenthesis.
[a] denotes significant difference between heights 1 and 2.
[b] denotes significant difference between heights 1 and 3.
[c] denotes significant difference between heights 1 and 4.
[d] denotes significant difference between heights 2 and 3.
[e] denotes significant difference between heights 2 and 4.
[f] denotes significant difference between heights 3 and 4.
* denotes significant difference between the shoe and barefoot conditions on the same landing height.
The definitions of variables are in appendix A.

Table 3. Means and standard deviations of ankle joint kinematic variables (Group 2).

Surface	Height	Cont	Max	Tmax	Min	Tmin	ROM	ContVel	MaxVel	TmaxVel
Shoe	1	-1.997	19.841	0.220	-3.131	0.199	22.972	73.699	257.141	0.033
		(2.981)	(1.076)	(0.055)	(2.009)	(0.183)	(3.076)	(25.665)	(28.459)	(0.004)
	2	-1.319	21.585	0.193	-2.032	0.157	23.617	205.781	326.495	0.036
		(3.833)	(1.125)	(0.041)	(3.854)	(0.059)	(2.730)	(58.986)	(44.121)	(0.017)
	3	-5.622	21.562	0.215	-5.622	0.000	27.184	389.584 [b,d]	473.690 [b]	0.021 [d]
		(5.170)	(2.318)	(0.049)	(5.170)	(0.000)	(3.221)	(19.957)	(24.790)	(0.007)
	4	-7.835	22.390	0.196	-8.771	0.080	31.162 [c,e]	548.367 [c,e,f]	660.024 [c,e,f]	0.010 [c,e]
		(8.190)	(3.747)	(0.057)	(6.726)	(0.139)	(3.813)	(185.545)	(170.389)	(0.008)
Barefoot	1	-6.972	21.381	0.195	-7.591	0.031	28.972	290.611 *	435.643 *	0.020
		(6.652)	(3.700)	(0.036)	(7.164)	(0.052)	(3.674)	(118.810)	(77.052)	(0.007)
	2	-11.075	21.694	0.240	-11.075	0.000	32.768 *	531.685 [a],*	630.789 [a],*	0.012 *
		(4.853)	(2.836)	(0.081)	(4.853)	(0.000)	(2.291)	(40.062)	(65.700)	(0.001)
	3	-14.247	21.649	0.170	-14.247	0.000	35.896 *	650.912 [b],*	807.347 [b,d],*	0.011
		(4.192)	(4.468)	(0.052)	(4.192)	(0.000)	(7.080)	(12.591)	(121.239)	(0.004)
	4	-15.754	21.823	0.178	-15.754	0.000	37.577 [c]	666.482 [c]	858.314 [c,e],*	0.014
		(7.846)	(3.121)	(0.043)	(7.846)	(0.000)	(5.936)	(87.387)	(110.575)	(0.004)

Note: Angle and ROM units are in degrees and units of time are in s.
Velocity units are in deg/s.
Standard deviation values are in parenthesis.
[a] denotes significant difference between heights 1 and 2.
[b] denotes significant difference between heights 1 and 3.
[c] denotes significant difference between heights 1 and 4.
[d] denotes significant difference between heights 2 and 3.
[e] denotes significant difference between heights 2 and 4.
[f] denotes significant difference between heights 3 and 4.
* denotes significant difference between the shoe and barefoot conditions on the same landing height.
The definitions of variables are in appendix A.

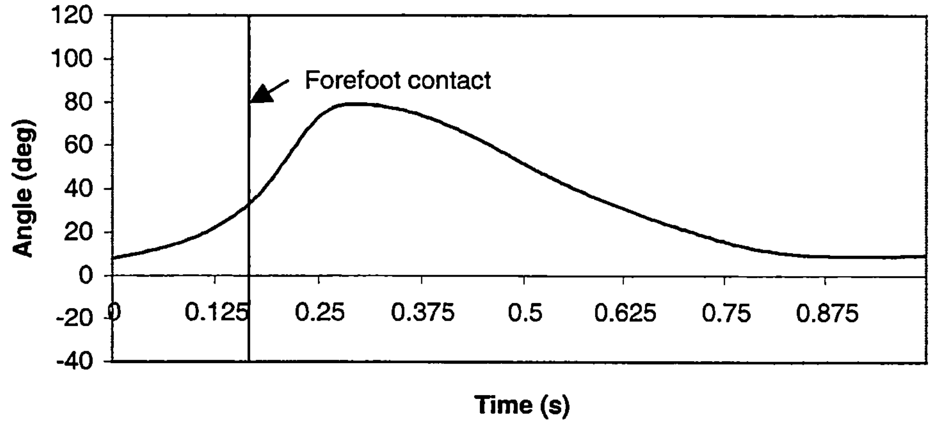
All heights with barefoot for the MaxVel were significantly different except for comparison between 60 and 75 cm. The landing barefoot at each height produced significantly greater maximum angular velocity than landing shoe at the same height. The barefoot landing at 45 cm showed significantly faster time to reach the MaxVel than the shoe condition at the same height.

Knee Joint

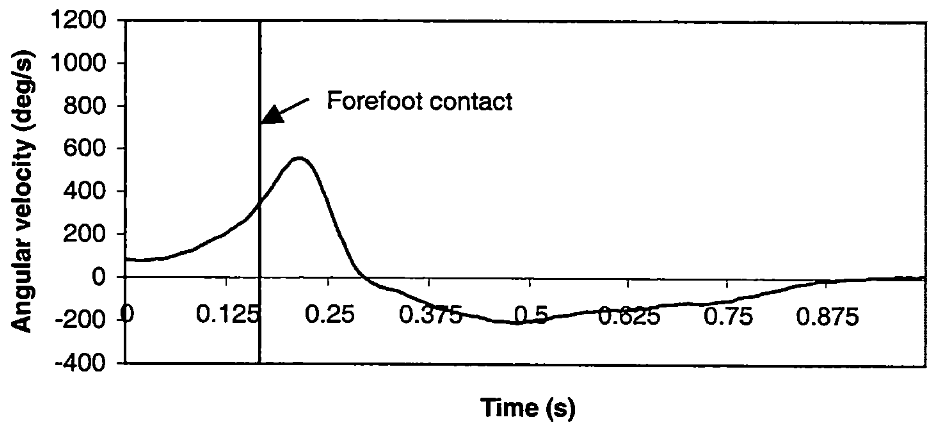
Representative curves of the knee joint angle and angular velocity are provided in Figure 4. Representative curves of the knee joint for barefoot landing at 60 cm are provided in Appendix F. An increasing knee angle indicates knee flexion and a decreasing knee angle indicates knee extension. Positive knee joint angular velocities are associated with angular knee flexion velocity and negative knee joint angular velocities are associated with knee joint extension velocity.

Group 1

A significant omnibus F was found for knee joint Max ($F = 2.75$, $p<0.05$), ROM ($F = 3.80$, $p<0.05$), and MaxVel ($F = 6.74$, $p<0.05$). Significant main effect of height was found for Max, ROM, and MaxVel. Only MaxVel showed interactions between height and surface conditions. No significant omnibus F was found for Cont, Min, Tmax, Tmin, ContVel, and TmaxVel.



(a) Joint angle



(b) Joint angular velocity

Figure 4. Representative knee joint curves for shoe at 60 cm (Group 1).

Increased Max knee angles were observed with increased landing heights. The post-hoc comparison revealed that the Max knee angle with shoes was significantly different between 30 and 75 cm, between 45 and 60 cm, and between 45 and 75 cm (Table 4). The Max angle at 30 cm with barefoot was significantly smaller than that at 60 and 75 cm. The post-hoc comparison showed the height of 75 cm in the shoe conditions produced significantly larger ROM than the heights of 30 and 45 cm. The ROM at 30 cm with barefoot was significantly smaller than that at 60 and 75 cm. MaxVel of 60 and 75 cm in the shoe conditions were greater than those of 30 and 45 cm. The heights of 60 and 75 cm with barefoot produced significantly greater MaxVel than 30 cm. The barefoot landing at 45 cm showed significantly greater MaxVel than the shoe landing at the same height.

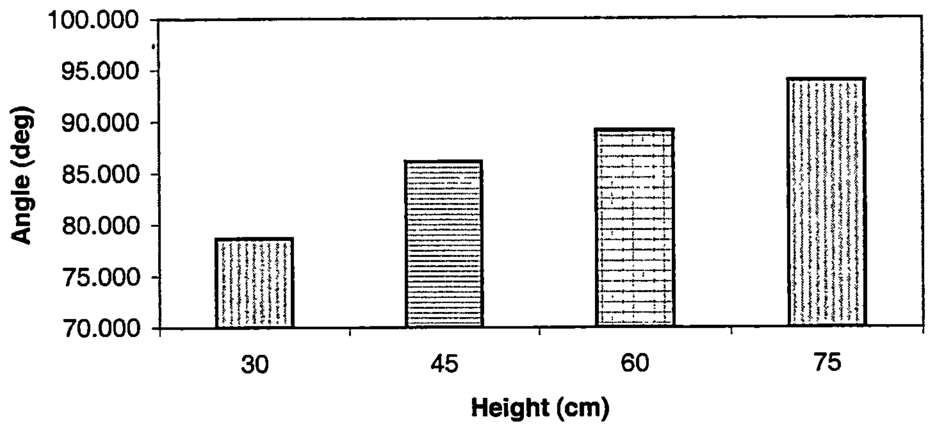
<u>Group 2</u>

The ANOVA results demonstrated a significant omnibus F for the knee joint Max angle ($F = 2.68$, $p<0.05$). A significant main effect of height was found for Max (Appendix H), no interactions and surface main effect were seen that. The post-hoc comparison showed that the height of 75 cm in both shoe and barefoot conditions revealed greater Max angle than the height of 30 cm (Figure 5).

Table 4. Means and standard deviations of knee joint kinematic variables (Group 1).

Surface	Height	Cont	Max	Tmax	Min	Tmin	ROM	ContVel	MaxVel	TmaxVel
Shoe	1	29.615	81.749	0.205	22.061	0.324	59.688	332.804	612.710	0.045
		(8.036)	(10.269)	(0.075)	(9.945)	(0.226)	(6.640)	(67.268)	(70.457)	(0.014)
	2	32.322	91.096	0.207	26.801	0.265	64.295	385.639	661.908	0.04
		(6.981)	(11.694)	(0.056)	(11.32)	(0.251)	(7.82)	(62.77)	(65.531)	(0.009)
	3	31.602	94.776 [d]	0.204	26.477	0.255	68.299 [d]	383.067	772.220 [b,d]	0.044
		(7.984)	(11.331)	(0.049)	(10.172)	(0.252)	(7.025)	(86.178)	(90.488)	(0.009)
	4	33.061	97.793 [c,e]	0.207	27.042	0.272	70.751 [c,e]	435.266	814.584 [c,e]	0.039
		(6.67)	(11.051)	(0.054)	(8.654)	(0.247)	(6.911)	(88.664)	(93.679)	(0.008)
Barefoot	1	26.953	79.051	0.190	20.744	0.297	58.308	321.236	575.618	0.047
		(7.612)	(11.029)	(0.063)	(6.991)	(0.214)	(7.852)	(52.380)	(64.592)	(0.008)
	2	28.032	86.785	0.193	22.103	0.293	64.682	357.270	661.327 *	0.047
		(6.541)	(11.454)	(0.048)	(9.057)	(0.233)	(8.077)	(56.445)	(68.570)	(0.007)
	3	31.483	94.789 [b]	0.204	23.679	0.296	71.110 [b]	418.455	705.492 [b]	0.043
		(5.218)	(12.383)	(0.052)	(9.109)	(0.312)	(9.156)	(78.355)	(67.067)	(0.007)
	4	32.344	97.660 [c]	0.198	24.359	0.287	73.301 [c]	426.975	751.067 [c]	0.043
		(5.280)	(12.786)	(0.048)	(8.935)	(0.288)	(9.790)	(67.232)	(80.036)	(0.007)

Note: Angle and ROM units are in degrees and units of time are in s.
Velocity units are in deg/s.
Standard deviation values are in parenthesis.
[a] denotes significant difference between heights 1 and 2.
[b] denotes significant difference between heights 1 and 3.
[c] denotes significant difference between heights 1 and 4.
[d] denotes significant difference between heights 2 and 3.
[e] denotes significant difference between heights 2 and 4.
[f] denotes significant difference between heights 3 and 4.
* denotes significant difference between the shoe and barefoot conditions on the same landing height.
The definitions of variables are in Appendix A.

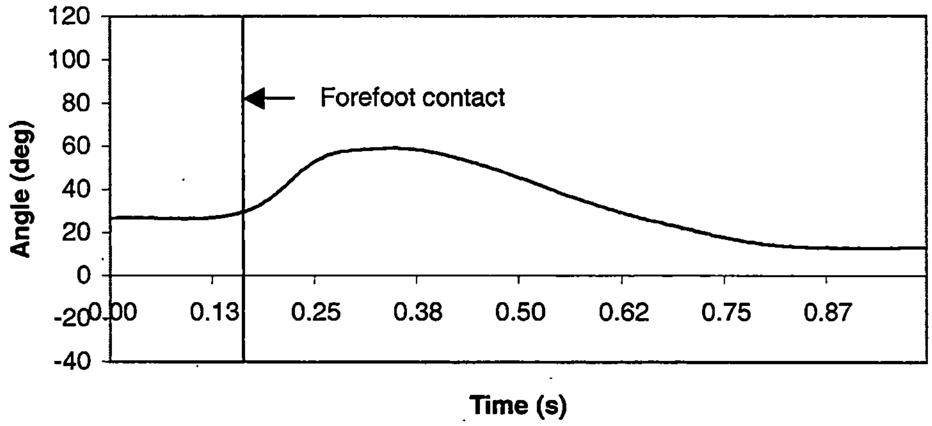


Note: Same shadow of the bar denotes significant difference ($p<0.05$).

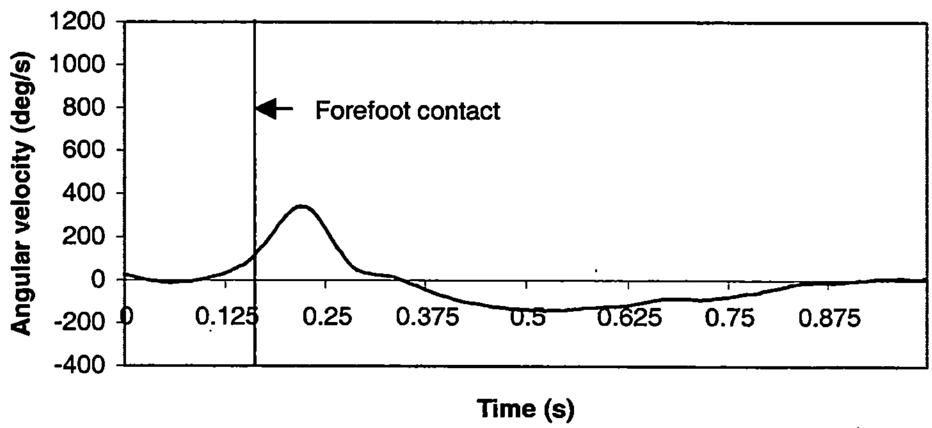
Figure 5. Maximum knee joint angle in the shoe conditions (Group 2).

Hip Joint

Representative curves of the hip joint angle and angular velocity are provided in Figure 6. Representative curves of the hip joint in the barefoot conditions at 60 cm are provided in Appendix F. An increasing hip angle indicates hip flexion and a decreasing hip angle indicates hip extension. Positive hip joint angular velocities are associated with hip angular flexion velocity and negative angular velocities are associated with hip joint extension velocity.



(a) Joint angle



(b) Joint angular velocity

Figure 6. Representative hip joint curves for shoe at 60 cm (Group 1).

Group 1

The ANOVA results showed significant omnibus F for hip joint Max ($F = 3.37$, $p<0.05$), ROM ($F = 7.23$, $p<0.05$), ContVel ($F = 2.78$, $p<0.05$), and MaxVel ($F = 10.35$, $p<0.05$). Significant main effect of height was found for Max, ROM, ContVel, and MaxVel. No interactions and surface main effect were found for those variables. No significant omnibus F was found for Cont, Min, Tmax, Tmin, and TmaxVel.

The post-hoc comparison showed that the Max angle at 75 cm with shoes was greater than that at 30 and 45 cm (Table 5). The height of 30 cm in the barefoot conditions produced significantly smaller Max angle than the heights of 60 and 75 cm. The ROM at 75 cm with shoes was significantly greater than that at 30, 45, and 60 cm. The height of 75 cm in the barefoot conditions produced significantly greater ROM than the heights of 30 and 45 cm. The ROM at 60 cm with barefoot was significantly greater than that at 30 cm.

The ContVel at 75 cm with shoes was significantly greater than that at 45 cm. The height of 75 cm with barefoot produced significantly greater ContVel than the heights of 30 and 45 cm. The ContVel at 30 cm in the barefoot conditions was significantly smaller than that at 60 cm. The MaxVel at 75 cm in the shoe conditions was significantly greater velocity than that at 30 and 45 cm. The height of 60 cm with shoes produced greater MaxVel than the heights of 30 and 45 cm. The height of 75 cm with barefoot was significantly greater MaxVel than the heights of 30 and 45 cm. The MaxVel at 60 cm with barefoot was significantly greater than that at 30 cm.

Table 5. Means and standard deviations of hip joint kinematic variables (Group 1).

Surface	Height	Cont	Max	Tmax	Min	Tmin	ROM	ContVel	MaxVel	TmaxVel
	1	35.214	73.058	0.232	29.889	0.286	43.169	146.057	397.449	0.052
		(8.718)	(14.024)	(0.087)	(9.198)	(0.258)	(8.708)	(76.674)	(68.837)	(0.016)
	2	36.052	80.990	0.237	31.866	0.250	49.124	160.387	438.061	0.054
Shoe		(5.878)	(16.121)	(0.07)	(9.033)	(0.3)	(10.09)	(47.573)	(77.743)	(0.014)
	3	34.125	88.382	0.248	30.073	0.238	58.309 [b,d]	167.530	551.804 [b,d]	0.053
		(7.324)	(17.923)	(0.093)	(9.035)	(0.269)	(11.757)	(54.013)	(81.491)	(0.010)
	4	35.864	97.105 [c,e]	0.264	31.741	0.241	65.364 [c,e]	204.956 [e]	601.838 [c,e]	0.049
		(6.541)	(17.799)	(0.102)	(6.941)	(0.266)	(14.833)	(38.062)	(80.375)	(0.009)
	1	34.427	74.281	0.225	29.325	0.294	44.956	130.537	382.572	0.062
		(9.115)	(20.443)	(0.080)	(8.889)	(0.227)	(13.439)	(65.566)	(67.295)	(0.023)
	2	35.281	85.381	0.237	30.518	0.252	54.863	158.447	470.516 [a]	0.056
Barefoot		(8.786)	(19.293)	(0.064)	(11.205)	(0.274)	(10.337)	(51.287)	(75.402)	(0.009)
	3	35.254	92.921 [b]	0.244	29.586	0.300	63.336 [b]	200.924 [b]	529.044 [b]	0.055
		(6.823)	(17.951)	(0.069)	(8.437)	(0.316)	(11.057)	(58.425)	(76.214)	(0.013)
	4	36.470	102.492 [c,e]	0.251	31.942	0.252	70.551 [c,e]	229.292 [c,e]	601.722 [c,e]	0.054
		(8.055)	(19.137)	(0.067)	(8.582)	(0.285)	(13.467)	(52.245)	(75.804)	(0.010)

Note: Angle and ROM units are in degrees and units of time are in s.
Velocity units are in deg/s.
Standard deviation values are in parenthesis.
[a] denotes significant difference between heights 1 and 2.
[b] denotes significant difference between heights 1 and 3.
[c] denotes significant difference between heights 1 and 4.
[d] denotes significant difference between heights 2 and 3.
[e] denotes significant difference between heights 2 and 4.
[f] denotes significant difference between heights 3 and 4.
* denotes significant difference between the shoe and barefoot conditions on the same landing height.
The definitions of variables are in Appendix A.

Group 2

A significant omnibus F was found for hip angular MaxVel ($F = 6.22$, $p<0.05$). A significant main effect of height was found for the MaxVel. The post-hoc comparison showed that the MaxVel at 75 cm in the shoe and the barefoot conditions were significantly greater than that at 30 and 45 cm. The height of 60 cm in the shoe and the barefoot conditions produced greater MaxVel than the height of 30 cm. Descriptive statistics for hip joint variables are listed in Appendix H.

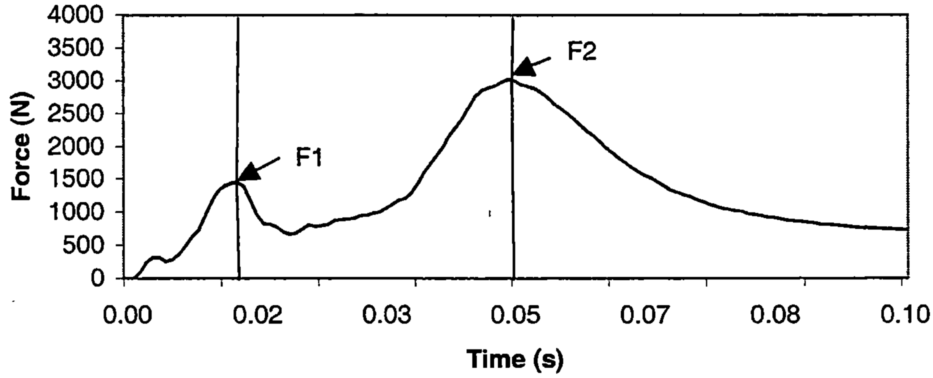
Kinetics

Vertical Ground Reaction Force

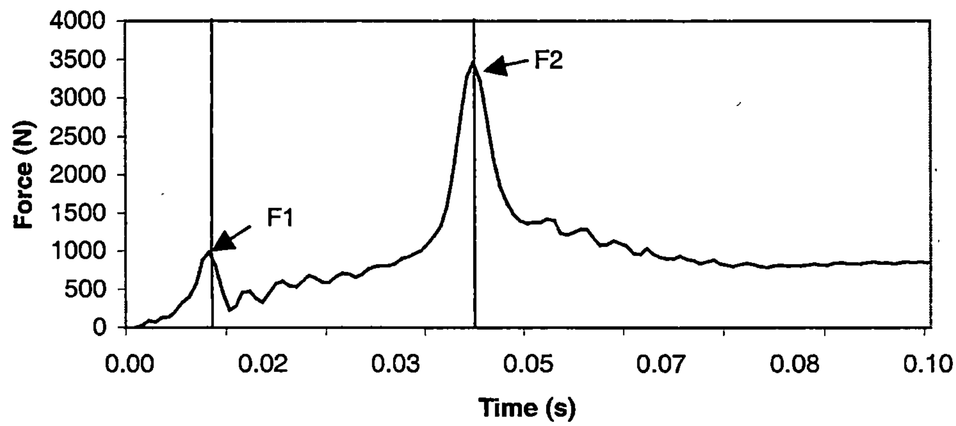
In this section, vertical ground reaction force and acceleration data are presented. Vertical GRF variables included the first (F1, forefoot contact) and the second (F2, heel contact) maximum VGRF, the time to F1 (T1) and F2 (T2), the loading rate of F1 (LrateF1) and F2 (LrateF2), and impulse of VGRF from contact to 100 ms (Imp100ms). F1 loading rate was computed as a ratio of F1 and T1. F2 loading rate was computed as ratio of (F2-Fmin)/(T2-Tmin). Representative VGRF curves are shown in Figure 7.

Group 1

Significant omnibus F was found for F1 ($F = 26.15$, $p<0.05$), F2 ($F = 4.01$, $p<0.05$), LrateF1 ($F = 3.95$, $p<0.05$), and Imp100ms ($F = 4.55$, $p<0.05$). Significant main height and surface effects were found for F1, F2, LrateF1, and Imp100ms. No significant omnibus was found for T1, T2, and LrateF2.



(a) VGRF curve for shoe at 60 cm



(b) VGRF curve for barefoot at 60 cm

Figure 7. Representative VGRF curves (Group 1).

Increased landing heights in the shoe and the barefoot landing were showed to cause significantly greater magnitude of F1. The height of 75 cm with shoes produced significantly greater F1 than the same height with barefoot (Figure 8). F2 at 75 cm with shoes and barefoot produced significantly greater forces than that at 30 cm.

LrateF1 at 75 cm in the shoe conditions revealed significantly greater loading rate than that at 30 cm. LrateF1 at 30 cm in the barefoot conditions was significantly smaller than that at 45, 60, and 75cm. Imp100ms at 75 cm with shoes produced significantly greater impulse than that at 30 and 45 cm. Imp100ms at 60 cm with shoes was significantly greater than that at 30 cm. For the barefoot, Imp100ms at 45, 60, and 75 cm was significantly greater than that at 30 cm (Table 6).

Group 2

Subjects who landed with the flatfoot landing technique did not reveal F1, T1, and LrateF1 during the experiment. A significant omnibus F was found for F2 ($F = 3.59$, $p<0.05$) and T2 ($F = 2.86$, $p<0.05$). Significant main effects of height and surface were found for F2 while significant main effect of surface was observed for T2 (Appendix H).

The post-hoc comparison showed that the barefoot conditions at 30 cm produced greater magnitude of F2 than the shoe conditions at the same height (Figure 9). T2 with shoes at 30, 45, and 60 cm was significantly faster than that with barefoot at each same landing height (Figure 10).

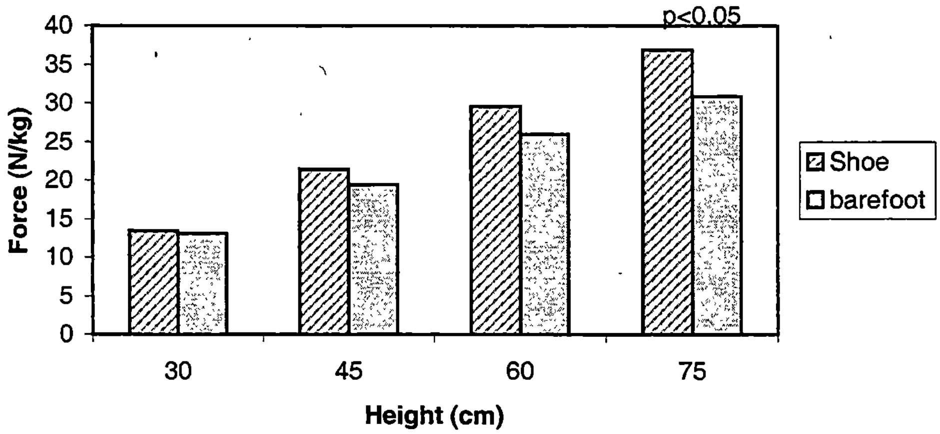


Figure 8. Mean F1 values at different heights (Group 1)

Significant difference was found between the surface conditions at each landing height.

Table 6. Means and standard deviations of vertical ground reaction force variables (Group 1).

Surface	Height	F1	T1	F2	T2	LrateF1	LrateF2	Imp100ms
Shoe	1	13.424	0.007	54.273	0.042	1953.058	1831.765	2.525
		(5.039)	(0.004)	(10.071)	(0.014)	(1086.067)	(952.811)	(0.327)
	2	21.460 [a]	0.008	59.279	0.044	2922.792	1965.419	2.671
		(3.432)	(0.003)	(13.118)	(0.013)	(1039.659)	(915.225)	(0.368)
	3	29.558 [b, d]	0.009	65.403	0.041	3592.578	2168.216	2.911 [b]
		(4.774)	(0.003)	(10.030)	(0.009)	(814.218)	(781.164)	(0.377)
	4	36.863 [c, e, f]	0.009	75.902 [c]	0.039	4546.078 [c]	2771.090	3.123 [c, e]
		(7.415)	(0.002)	(17.894)	(0.008)	(1030.121)	(1184.135)	(0.460)
Barefoot	1	13.104	0.007	65.202	0.050	2623.742	1692.260	2.237
		(3.590)	(0.004)	(18.683)	(0.012)	(1667.453)	(811.473)	(0.267)
	2	19.415 [a]	0.006	76.169	0.045	4370.646 [a]	2126.449	2.603 [a]
		(4.476)	(0.003)	(21.535)	(0.010)	(2605.665)	(937.333)	(0.372)
	3	25.992 [b, d]	0.007	80.965	0.045	5095.213 [b]	2305.932	2.775 [b]
		(5.848)	(0.003)	(27.035)	(0.009)	(3215.794)	(1162.897)	(0.382)
	4	30.897 [c, e, f, *]	0.008	91.241 [c]	0.043	5338.847 [c]	2857.155	2.879 [c]
		(6.236)	(0.004)	(27.029)	(0.007)	(2564.041)	(1262.236)	(0.584)

Note: Force unit is in N/kg and time unit is in s.
Loading rate unit is in N/kg/s.
Impulse unit is in (N/kg)·s.
Standard deviation values are in parenthesis.
[a] denotes significant difference between heights 1 and 2.
[b] denotes significant difference between heights 1 and 3.
[c] denotes significant difference between heights 1 and 4.
[d] denotes significant difference between heights 2 and 3.
[e] denotes significant difference between heights 2 and 4.
[f] denotes significant difference between heights 3 and 4.
* denotes significant difference between the shoe and barefoot conditions on the same landing height.
The definitions of variables are in Appendix A.

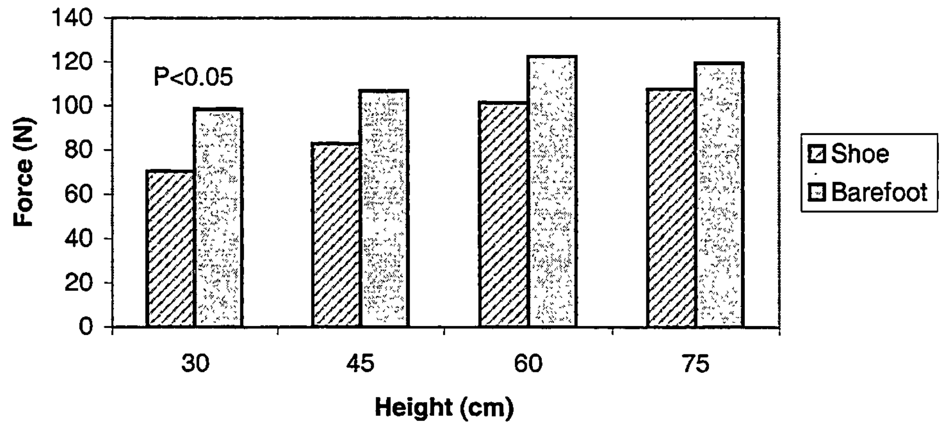


Figure 9. Mean F2 values at different heights (Group 2)

Significant difference was found between the surface conditions at each landing height.

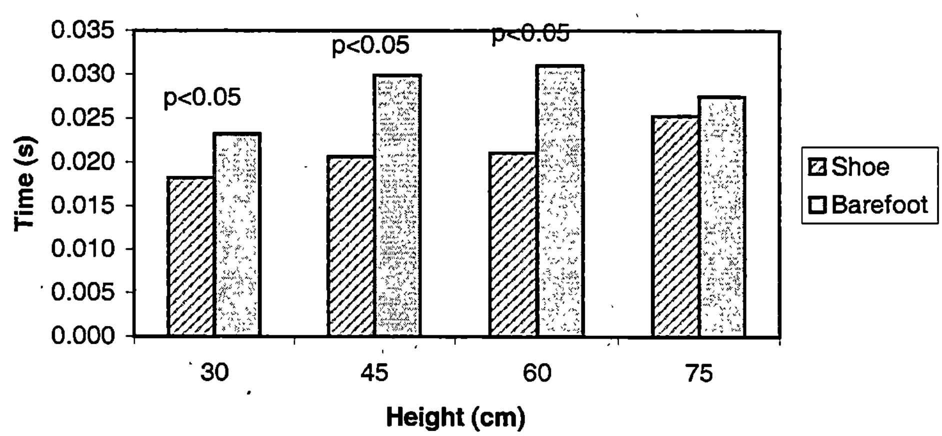


Figure 10. Mean T2 values at different heights (Group 2)

Significant difference was found between the surface conditions at each landing height.

Acceleration

Acceleration variables included maximum head acceleration (AccHead), the time to AccHead (TaccHead), the first (AccTibia1) and second (AccTibia2) maximum tibia accelerations, the time to AccTibia1 (TaccTibia1) and AccTibia2 (TaccTibia2), and shock attenuation index (AtteIndex). The AtteIndex is calculated as:

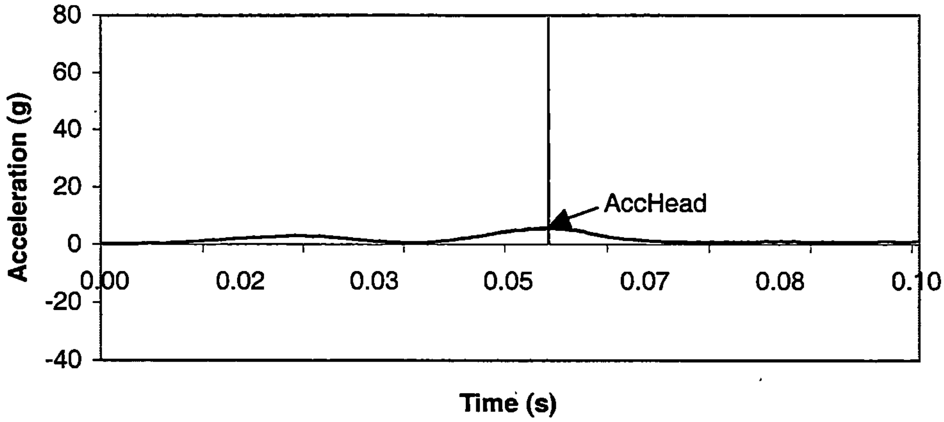
$$AtteIndex = (1 - \frac{AccHead}{AccTibia2}) \times 100$$

Typical head and tibia acceleration curves with shoes at 60 cm are provided in Figure 11; Representative head and tibia acceleration curves with barefoot at 60 cm are provided in Appendix F.

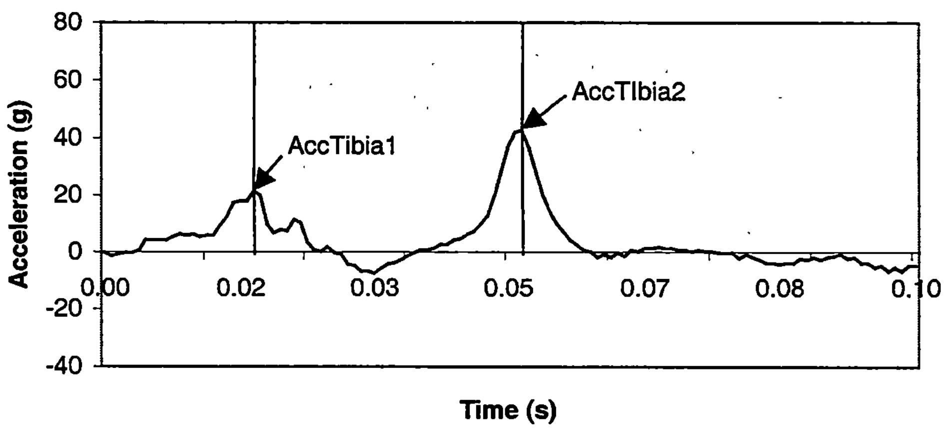
Group 1

Significant omnibus F was found for AccHead ($F = 4.41$, $p<0.05$), AccTibia1 ($F = 12.03$, $p<0.05$), AccTibia2 ($F = 8.10$, $p<0.05$), and AtteIndex ($F = 6.24$, $p<0.05$). Significant main effects of height and surface were found for AccHead, AccTibia1, and AccTibia2. Significant main of surface effect was found for AtteIndex.

For the shoe condition, the post-hoc comparison showed that the AccHead at 75 cm was significantly greater than that at 30 and 45 cm (Table 7). The maximum head acceleration at 75 cm in the shoe conditions was significantly greater than that in the barefoot conditions at the same height.



(a) Head acceleration



(b) Tibia acceleration

Figure 11. Representative acceleration curves for shoe at 60 cm (Group 1).

Table7. Means and standard deviations of acceleration variables (Group 1).

Surface	Height	AccHead	TaccHead	AccTibia1	TaccTibia1	AccTibia2	TaccTibia2	AtteIndex
	1	2.571	0.052	7.821	0.013	18.251	0.045	84.363
		(0.763)	(0.011)	(5.219)	(0.007)	(8.170)	(0.012)	(5.829)
	2	3.301	0.053	12.073	0.016	23.816	0.046	85.235
Shoe		(1.079)	(0.014)	(4.424)	(0.005)	(9.582)	(0.009)	(4.131)
	3	3.631 [b]	0.050	17.965 [b, d]	0.016	28.508	0.044	87.009
		(0.974)	(0.010)	(6.074)	(0.005)	(6.705)	(0.007)	(3.167)
	4	4.463 [c, e]	0.045	22.840 [c, e, f]	0.016	38.240 [c, e]	0.043	88.099
		(1.180)	(0.006)	(7.631)	(0.004)	(9.410)	(0.007)	(2.844)
	1	2.305	0.059	7.473	0.017	30.101	0.054	90.608 *
		(1.010)	(0.013)	(2.382)	(0.006)	(12.868)	(0.008)	(5.625)
	2	2.687	0.052	10.843	0.016	37.688	0.050	91.730 *
Barefoot		(1.141)	(0.009)	(2.991)	(0.005)	(15.471)	(0.008)	(4.874)
	3	2.961	0.050	14.656 [b]	0.016	47.494 [b], *	0.049	92.076 *
		(1.108)	(0.011)	(4.278)	(0.005)	(24.881)	(0.007)	(4.567)
	4	3.220 *	0.047	17.454 [c, e], *	0.017	63.943 [c, e, f], *	0.047	93.958*
		(0.936)	(0.007)	(3.962)	(0.005)	(27.666)	(0.005)	(3.010)

Note: Acceleration unit is in g and time unit is in s.
Shock attenuation index unit is in %.
Standard deviation values are in parenthesis.
[a] denotes significant difference between heights 1 and 2.
[b] denotes significant difference between heights 1 and 3.
[c] denotes significant difference between heights 1 and 4.
[d] denotes significant difference between heights 2 and 3.
[e] denotes significant difference between heights 2 and 4.
[f] denotes significant difference between heights 3 and 4.
* denotes significant difference between the shoe and barefoot conditions on the same landing height.
The definitions of variables are in Appendix A.

Increased landing heights caused increased AccTibia1 values. The AccTibia1 at all heights in the shoe conditions was significantly different except for comparisons between 30 and 45 cm. AccTibia1 with barefoot at 75 cm was significantly greater than that at 30 and 45 cm. The barefoot at 60 cm produced greater AccTibia1 than the barefoot at 30 cm. The shoe condition at 75 cm produced greater AccTibia1 than the barefoot condition at the same height.

The AccTibia2 at 75 cm in the shoe conditions was significantly greater than that at 30 and 45 cm. For the barefoot condition, the height of 75 cm produced significantly greater AccTibia2 than 30, 45, and 60 cm. AccTibia2 at 60 and 75 cm with barefoot were significantly greater than those with shoes at each same height. The shock attenuation index with barefoot at all heights were significantly greater than those with shoes at each height (Figure 12).

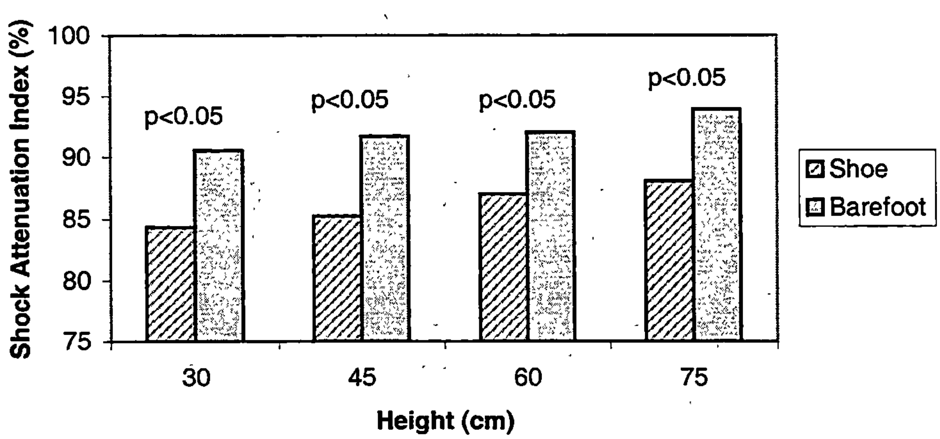


Figure 12. Mean shock attenuation index values at different heights (Group 1) Significant difference was found between the surface conditions at each landing height.

Group 2

A significant omnibus F was found for AccTibia2 ($F = 5.51$, $p<0.05$) and TaccTibia2 ($F = 3.04$, $p<0.05$). Significant main effects of height and surface were found for AccTibia2. A significant surface effect was also found for TaccTibia2.

For the barefoot condition, the post-hoc comparison showed that the AccTibia2 at 30 cm was significantly smaller than that at 60 and 75 cm (Appendix H). The barefoot conditions at 60 and 75 cm produced significantly greater AccTibia2 than the shoe conditions at the same height (Figure 13). The TaccTibia2 with shoes at 45 and 60 cm were significantly less than those with barefoot at the same height.

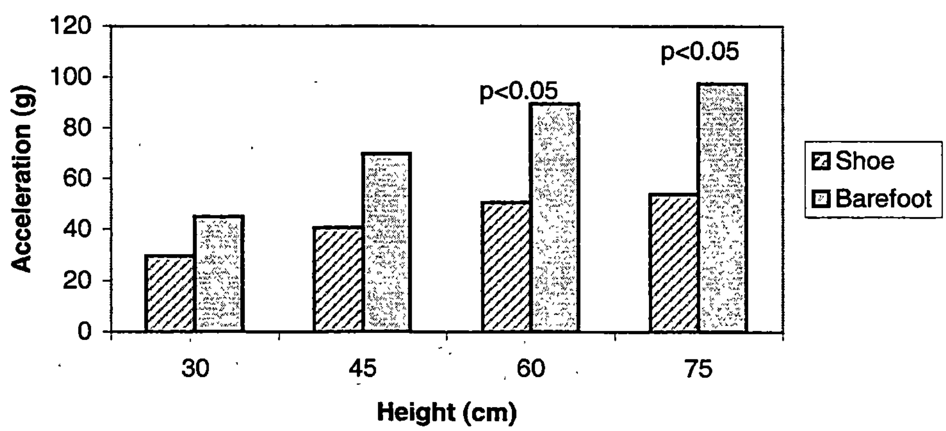


Figure 13. Mean AccTibia2 values at different heights (Group 2)

Significant difference was found between the surface conditions at each landing height.

Chapter V

Discussion and Conclusions

Discussion

The purpose of this study was to investigate impact force and shock attenuation during landings from different heights on different surface conditions. The vertical ground reaction force, accelerometer data, and kinematic variables were examined and analyzed. In this chapter only the results of group 1 will be discussed.

The first maximum VGRF (F1) significantly varied with increased heights and changed surface conditions. The F1 values at all landing heights were significantly different from each other for both surface conditions. F1 increased from 13.42 N/kg at 30 cm to 36.86 N/kg in the shoe conditions, and from 13.10 N/kg at 30 cm to 30.90 N/kg at 75 cm in the barefoot conditions (Table 6). The effect of shoe condition for F1 was statistically significant at 75 cm level. At the other heights, F1 did not show significant changes, but demonstrated a trend of greater values in the shoe conditions than that in the barefoot conditions. This result is initially counterintuitive and greater F1 values for the barefoot are expected since impact forces are expected to increase without shoe protection. The occurrence of F1 is associated with the forefoot contact with the ground. The contact and maximum ankle angular velocities may indicate how the forefoot and ankle joint are controlled at and after the touchdown. Further examinations of the ankle angular kinematics suggest that the contact and maximum angular velocities at 75 cm with the shoe landing were greater than those with the barefoot landing (Table 2). These data may indicate that the ankle plantarflexors are less active in the shoe conditions. This result may also suggest that the subjects were sensitive to the changes of surfaces at the forefoot contact, and were able to cope with such changes with neuromuscular intervention.

The present study presented a different F1 pattern than has been previously reported in walking and running studies. Cavanagh et al. [3] examined impact force during walking with three different shoes (Army boot, Leather street shoe, and Crepe soled casual shoe) and barefoot. The first maximum VGRF in the barefoot condition (0.55 BW) was significantly greater than that in any shoe conditions. F1 with army boots, leather street shoes, and crepe soled casual shoes were 0.37, 0.27, and 0.25 BW, respectively. Lafortune et al. [20] reported a significant difference for the initial peak of VGRF between the barefoot and shoe conditions (street shoes and athletic shoes) during walking. F1 with the barefoot (0.69 BW) was significantly greater than that with the street shoes (0.48 BW) as well as with the athletic shoes (0.44 BW). However, F1 did not show any significance between shoe and barefoot in running studies. F1 in barefoot running (2.25 BW) was slightly higher than that in the shoe running (2.11 BW) for one subject [4]. Wit et al. [38] found that the difference F1 was not significant, but F1 in the barefoot running showed slightly higher magnitude than that in the shoe running.

The second maximum VGRF (F2) demonstrated a different trend across the surface conditions compared with the changes of F1. Even though they were not significant, the F2 values for the barefoot were generally greater than those for the shoe conditions (Table 6). The F2 event occurs at the time of heel contact with the ground after the initial forefoot contact. It was found that VGRF with barefoot was 1.1 times

(4.3 BW) greater than that with shoes during netball landings [35]. This reversal of responses of the shoe and barefoot was not observed in running studies. In the study conducted by Wit et al. [38], the F2 values between shoe and barefoot running were same (2.9 BW) at a speed of 4.5 m/s.

An explanation of the mechanisms of different VGRF responses at the forefoot contact and heel contact in the shoe and barefoot conditions are attempted below. F1 with shoe was slightly greater than that with barefoot whereas F2 with barefoot was slightly greater than that with shoes. Impact forces in landing usually occur within 50 ms that is beyond the human reaction time. Any attempt to reduce impact forces during the impact phase is preprogrammed by the neuromuscular system prior to the touchdown [23]. The preset neuromuscular program intension is rather effective in reducing F1 in the barefoot conditions. The heel contact occurs at a later time than forefoot contact. The neuromuscular intervention may be therefore, less effective reducing F2 at the heel contact than at the forefoot contact. The reaction of kinematic variables could be indicative of muscular responses. In this study, the contact angle and the range of motion of the ankle, knee, and hip joints did not show any significant differences across surface conditions. It is, therefore, suggested that the shoe provided an additional capacity to attenuate impact forces.

The loading rate of F1 (LrateF1) indicates how fast mechanical load is applied to the body from contact to F1. LrateF1 at 75 cm with shoes was significantly faster than that at 30 cm (Table 6). Even though there was no statistical difference for LrateF1 across surface conditions, LrateF1 in the barefoot conditions presented a trend of greater values than that in the shoe conditions. This result is in agreement with the running studies conducted by Wit et al. [38] and De Clercq et al. [4]. The barefoot running produced greater F1 loading rate than the shoe running.

As mentioned early, increased first and second maximum VGRF were observed with increased landing heights. In the study conducted by Dufek and Bates [7], the landing height was a significant main effect for F1. F1 values at 40, 60, and 100 cm were 1.23, 1.31, and 2.15 BW, respectively. McNitt-Gray [24] reported increased VGRF magnitude with increased landing height. The VGRF was 4.2, 6.4, and 9.1 BW for recreational athletes, and 3.9, 6.3, and 11.0 BW for gymnastic athletes landings from 32, 72, and 128 cm, respectively. Ozguven et al. [29] reported that greater VGRF values were associated with increased heights. Subjects landing from 2.55 m produced VGRF ranged from 8.2 to 11.7 BW whereas subjects who landing from 0.45 m produced VGRF ranged from 5.0 to 7.0 BW.

The maximum head acceleration (AccHead) significantly demonstrated minimum amount of changes with changes in heights and surfaces. AccHead ranged from 2.57 g at 30 cm to 4.46 g at 75 cm in the shoe conditions, and from 2.30 g at 30 cm to 3.22 g at 75 cm in the barefoot conditions. Only AccHead with shoes was statistically greater than that with barefoot at 75 cm. AccHead with shoe displayed statistically significant increases with increased height, however the increases were incredibly small. The AccHead values with barefoot remained relatively constant across heights. This finding is in partial agreement with several previous studies [15, 33, 39]. The maximum head acceleration was shown to be constant during barefoot walking [39]. During treadmill running, the maximum head acceleration did not change with increased treadmill speed

[15, 33]. The constant AccHead values indicate that a body serves as a low pass filter and shock absorber during landings.

The first maximum tibia acceleration (AccTibia1) demonstrated a similar trend as F1 of VGRF across surface and height conditions. AccTibia1 showed significantly greater changes with increased heights in the shoe and barefoot conditions. AccTibia1 with shoe demonstrated generally greater values than those with barefoot, with statistically significant difference found between the shoes and barefoot at 75 cm. AccTibia1 occurs at the forefoot contact when F1 is observed. As mentioned early, changes in surface conditions and corresponding preprogrammed neuromuscular responses could be responsible for the similar trends of AccTibia1 and F1 across the surface conditions.

The second maximum tibia acceleration (AccTibia2) revealed statistical differences across height and surface conditions. AccTibia2 occurs at the time of the heel contact when F2 is observed. The AccTibia2 values increased from 18.25 g at 30 cm to 38.24 g at 75 cm, and from 30.10 g at 30 cm to 63.94 g at 75 cm with shoe and barefoot, respectively. AccTibia2 displayed a different pattern compared with the AccTibia1: the barefoot landing was significantly greater than the shoe landing at 60 and 75 cm. At the same time, kinematic results of lower extremity joints did not show any significant changes at these heights across the surface conditions. The contact angle and range of motion of ankle, knee, and hip joint did not change significantly across surface conditions. Due to the preset neuromuscular program, ankle plantarflexors were more active in the barefoot conditions than in the shoe conditions. Such a neuromuscular intervention has a greater effect on impact attenuation at the forefoot contact than at the heel contact because the heel contact occurs at a much later time than the forefoot contact. The smaller AccTibia2 values with shoe at 60 and 75 cm indicated that shoes added additional cushioning capacity in comparison to the barefoot conditions. However, the peak calcaneal and tibial accelerations did not show any significant difference across the three surface conditions in the Gross and Nelson 's study [13]. The average of peak calcaneus and tibia accelerations across the three surfaces was 20.8 and 14.3 g, respectively. Because the subjects were asked to land from a vertical jump, the input energy and landing heights were not controlled in the study, which could influence the results.

The AccHead values were much lower than the AccTibia values. The AccHead and AccTibia1 with shoe were 4.46 and 22.84 g at 75 cm, respectively. Similar differences were found for the barefoot landings. Shorten and Winslow [33] reported that the head acceleration was much less than the tibia acceleration at higher frequencies (above 6 Hz) whereas the head acceleration was much higher than the tibia acceleration at lower frequencies (below 6 Hz). The peak head acceleration was constant across a range of impact shock levels. Wosk and Voloshin [39] also indicated that the peak forehead acceleration was less than the peak tibia acceleration. It was suggested that the body serves as a filter minimizing the impact shock transmitted to the head. The shock attenuation index (AtteIndex) indicates that how much impact shock is attenuated by the human body. A higher AtteIndex value indicates greater shock attenuation while a smaller AtteIndex indicates lesser shock attenuation. The result demonstrated that the AtteIndex with barefoot was significantly greater than those with shoe at all landing heights (Table 7). The AtteIndex, for example, was 87 and 92 % for the shoe and barefoot at 60 cm, respectively. This result suggested that impact shock in the barefoot condition was more attenuated than in the shoe conditions. It is logical to assume that the shoes can provide additional impact shock. Impact shock may be attenuated through passive structures such as bones and soft tissues [39]. Impact shock can also be minimized by active muscle contraction. Subjects may change their landing strategies in order to protect their body from injury in the barefoot landings. Even though the kinematic results did not show any significant changes across the surface conditions, they seemed to be more cautious in the barefoot conditions than in the shoe conditions.

Conclusions

For the vertical ground reaction force, four variables (F1, F2, LrateF1, and Imp100ms) showed significant height effect. Greater values of these four variables increased with increased landing heights. F1 values with shoe were slightly greater than that of the barefoot conditions. On the other hand, the barefoot conditions produced greater F2 than the shoe conditions even though the results were not significant. The ankle, knee, and hip joint kinematic variables also showed a similar pattern. The range of motion and the maximum angular velocity of these joints increased with increased landing heights. At the forefoot contact, it is suggested that the ankle muscles were more active in the barefoot conditions than in the shoe conditions, therefore they played an important role in impact attenuation. It is also suggested that the shoes provided an additional cushion to minimize impact forces during landings.

The accelerometer results indicated four significant variables: AccHead, AccTibia1, AccTibia2, and AtteIndex. These variables except for AccHead demonstrated greater values with increased heights. The increased values of the

AccHead were relatively small while the AccTibia changes were much more significant. It is suggested that the body serves as a filter minimizing impact shock transmission to the head. The values of the AccTibia1 with shoes were greater than those with barefoot conditions whereas the AccTibia2 values with shoes were smaller than those with barefoot. These results along with the results of VGRF suggest that the shoe added a substantial amount of cushion and impact shock attenuation. The AtteIndex values in the barefoot conditions were also greater than those in the shoe conditions.

Recommendations for further studies can be derived from the experiences of this study. An accelerometer needs to be carefully and securely attached to subjects. In this study, the accelerometers were attached to the tibia and forehead of the subjects using athletic tape and Velcro straps. During the experiment, repetitive landing performances sometimes caused the Velcro straps to loosen up, therefore induced noisy signals of accelerations. It would be ideal to find a better way to fix an accelerometer to the skin of subjects. Subject populations of this study were healthy and active, but some of them were not skilled in jumping and landing. It would be more interesting how skilled athletes would attenuate impact shock with using their consistent landing techniques.

This study presented accurate information of the impact force, accelerometer data, and kinematics regarding to different surface conditions from different heights during landings. Future studies need to explore neuromuscular changes of the human body in impact attenuation during landing activities. It is necessary to examine the relationship between muscle activities of lower extremity joints and impact shock attenuation during landing activities.

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APPENDICES

APPENDIX A

DEFINITIONS OF VARIABLES

DEFINITIONS OF VARIABLES

Kinematics

Cont	Contact joint angle at ground contact
Max	Maximum joint angle
Tmax	Time to maximum joint angle
Min	Minimum joint angle
Tmin	Time to minimum joint angle
ROM	Range of motion of joint
ContVel	Angular joint velocity at ground contact
MaxVel	Angular joint maximum velocity
TmaxVel	Time to angular joint maximum velocity

VGRF

F1	First maximum vertical ground reaction force
T1	Time to first maximum vertical ground reaction force
F2	Second maximum vertical ground reaction force
T2	Time to second maximum vertical ground reaction force
LrateF1	Loading rate of the first maximum vertical ground reaction force
LrateF2	Loading rate of the second maximum vertical ground reaction force
Imp100ms	Impulse of vertical ground reaction force from contact to 100 ms

Acceleration

AccHead	Maximum head acceleration
TaccHead	Time to maximum head acceleration
AccTibia1	First maximum tibia acceleration
TaccTibia1	Time to the first maximum tibia acceleration
AccTibia2	Second maximum tibia acceleration
TaccTibia2	Time to the second maximum tibia acceleration
AtteIndex	Shock attenuation index

APPENDIX B

SUBJECT INFORMATION

Table 8. Subject information

Group	Subject	Age	Body Weight (kg)	Height (cm)
1	1	19	72.28	182.88
	2	20	78.03	177.8
	3	19	82.68	187.96
	4	28	81.39	187.96
	5	21	55.33	172.72
	6	21	71.05	180.34
	7	18	88.00	187.96
	8	20	73.06	180.34
	9	20	84.93	190.5
	10	18	83.16	180.34
Mean		20.4	76.99	182.88
S.D.		2.88	9.52	5.61
2	1	30	72.38	180.34
	2	21	86.38	175.26
	3	21	74.94	182.88
Mean		24	77.90	179.49
S.D.		5.2	7.45	3.87

APPENDIX C

KINEMATIC DATA

Table 9. Subject means and standard deviations of ankle joint variables (Group 1).

Subj	Cond	Cont	Max	Tmax	Min	Tmin	ROM	ContVel	MaxVel	TmaxVel
1	1	-21.158	27.826	0.178	-21.158	0.000	48.984	332.752	822.666	0.029
		(4.674)	(2.254)	(0.017)	(4.674)	(0.000)	(5.642)	(268.990)	(128.794)	(0.012)
	2	-13.057	31.486	0.211	-13.057	0.000	44.543	593.577	702.967	0.016
		(4.902)	(1.586)	(0.045)	(4.902)	(0.000)	(3.410)	(121.814)	(39.084)	(0.008)
	3	-25.262	31.691	0.233	-25.262	0.000	56.953	321.261	1035.753	0.030
		(6.180)	(1.572)	(0.072)	(6.180)	(0.000)	(6.050)	(312.203)	(53.295)	(0.007)
	4	-15.443	38.147	0.281	-15.443	0.000	53.59	886.838	1185.902	0.013
		(12.287)	(14.832)	(0.111)	(12.287)	(0.000)	(22.832)	(171.805)	(138.020)	(0.008)
	5	-19.952	26.390	0.156	-19.952	0.000	46.342	523.228	824.585	0.020
		(7.069)	(1.618)	(0.022)	(7.069)	(0.000)	(6.519)	(245.541)	(30.028)	(0.014)
	6	-22.547	23.554	0.176	-22.547	0.000	46.101	663.317	943.682	0.018
		(5.420)	(1.505)	(0.034)	(5.420)	(0.000)	(5.724)	(203.491)	(60.223)	(0.006)
	7	-14.673	27.664	0.196	-14.673	0.000	42.337	954.680	1077.978	0.008
		(9.352)	(1.849)	(0.058)	(9.352)	(0.000)	(10.284)	(112.418)	(75.370)	(0.007)
	8	-25.392	27.832	0.238	-25.392	0.000	53.224	693.255	1096.425	0.018
		(6.352)	(2.564)	(0.094)	(6.352)	(0.000)	(5.928)	(221.926)	(160.177)	(0.010)
2	1	-31.363	9.542	0.410	-31.363	0.000	40.905	541.859	776.305	0.018
		(6.230)	(2.086)	(0.217)	(6.230)	(0.000)	(6.942)	(124.115)	(94.946)	(0.003)
	2	-27.162	11.535	0.226	-27.162	0.000	38.697	717.213	894.856	0.012
		(6.059)	(1.813)	(0.098)	(6.059)	(0.000)	(7.607)	(98.570)	(88.746)	(0.006)
	3	-31.898	10.284	0.194	-31.898	0.000	42.182	607.041	967.331	0.018
		(4.898)	(1.158)	(0.046)	(4.898)	(0.000)	(5.655)	(190.901)	(45.531)	(0.007)
	4	-33.333	10.258	0.140	-33.333	0.000	43.591	856.430	1217.495	0.012
		(5.851)	(0.730)	(0.019)	(5.851)	(0.000)	(5.635)	(155.240)	(69.951)	(0.005)
	5	-32.733	11.099	0.185	-32.733	0.000	43.832	516.166	806.890	0.019
		(5.793)	(2.330)	(0.010)	(5.793)	(0.000)	(6.898)	(141.659)	(68.132)	(0.008)
	6	-31.075	12.469	0.169	-31.075	0.000	43.544	587.856	912.277	0.019
		(4.013)	(2.024)	(0.015)	(4.013)	(0.000)	(5.610)	(144.905)	(56.028)	(0.006)
	7	-33.208	11.403	0.173	-33.208	0.000	44.611	733.103	1076.460	0.015
		(5.279)	(1.338)	(0.074)	(5.279)	(0.000)	(4.498)	(158.991)	(83.295)	(0.007)
	8	-30.453	12.811	0.247	-30.453	0.000	43.264	621.042	991.186	0.017
		(7.656)	(11.021)	(0.200)	(7.656)	(0.000)	(16.195)	(220.235)	(131.139)	(0.010)

Table 9. (Continued).

Subj	Cond	Cont	Max	Tmax	Min	Tmin	ROM	ContVel	MaxVel	TmaxVel
3	1	-10.128	22.353	0.142	-11.657	0.075	34.010	637.595	745.427	0.008
		(13.529)	(1.433)	(0.020)	(10.851)	(0.184)	(9.847)	(232.391)	(256.506)	(0.009)
	2	-11.486	28.513	0.193	-11.486	0.000	39.998	780.644	893.862	0.009
		(6.815)	(2.231)	(0.048)	(6.815)	(0.000)	(8.816)	(134.278)	(49.923)	(0.008)
	3	-20.110	29.176	0.191	-20.110	0.000	49.286	677.182	1083.655	0.016
		(7.646)	(3.122)	(0.025)	(7.646)	(0.000)	(8.525)	(136.799)	(197.935)	(0.008)
	4	-4.177	30.736	0.195	-6.758	0.194	37.494	894.739	1040.554	0.006
		(15.629)	(0.868)	(0.058)	(12.443)	(0.300)	(12.823)	(274.650)	(275.758)	(0.009)
	5	-21.339	22.611	0.165	-21.339	0.000	43.950	518.145	784.843	0.021
		(3.763)	(2.581)	(0.022)	(3.763)	(0.000)	(5.076)	(139.267)	(41.660)	(0.006)
	6	-25.854	26.870	0.244	-25.854	0.000	52.724	381.573	928.712	0.027
		(1.742)	(0.891)	(0.071)	(1.742)	(0.000)	(2.262)	(38.834)	(33.454)	(0.002)
	7	-15.936	26.826	0.278	-16.099	0.118	42.926	648.239	933.262	0.016
		(11.237)	(2.246)	(0.073)	(10.883)	(0.265)	(9.998)	(228.008)	(57.756)	(0.011)
	8	-14.552	24.586	0.237	-15.157	0.120	39.744	712.417	998.636	0.014
		(12.600)	(2.889)	(0.060)	(11.328)	(0.268)	(13.408)	(184.513)	(99.815)	(0.010)
4	1	-6.617	24.377	0.249	-6.617	0.000	30.994	468.096	621.913	0.013
		(6.403)	(1.817)	(0.048)	(6.403)	(0.000)	(6.337)	(117.612)	(57.395)	(0.010)
	2	-5.550	25.808	0.200	-5.550	0.000	31.358	614.959	705.155	0.009
		(4.165)	(0.637)	(0.045)	(4.165)	(0.000)	(3.991)	(184.017)	(115.606)	(0.008)
	3	-9.762	24.323	0.195	-9.762	0.000	34.085	709.430	846.530	0.010
		(3.076)	(1.627)	(0.047)	(3.076)	(0.000)	(3.155)	(209.281)	(67.385)	(0.007)
	4	-15.889	23.436	0.188	-15.889	0.000	39.326	644.512	983.773	0.014
		(8.868)	(1.455)	(0.031)	(8.868)	(0.000)	(8.820)	(166.002)	(128.938)	(0.009)
	5	-5.082	26.843	0.192	-7.216	0.120	34.059	540.994	672.345	0.011
		(12.425)	(2.633)	(0.056)	(8.070)	(0.268)	(8.691)	(133.073)	(146.698)	(0.009)
	6	-10.198	25.470	0.240	-10.198	0.000	35.668	523.750	725.755	0.016
		(2.253)	(1.090)	(0.058)	(2.253)	(0.000)	(3.057)	(155.690)	(54.578)	(0.007)
	7	-14.368	27.473	0.254	-14.368	0.000	41.841	541.721	891.336	0.018
		(5.657)	(2.064)	(0.038)	(5.657)	(0.000)	(6.518)	(194.276)	(39.108)	(0.009)
	8	-19.768	27.227	0.277	-19.768	0.000	46.995	651.380	1030.238	0.018
		(3.624)	(1.519)	(0.088)	(3.624)	(0.000)	(3.492)	(161.554)	(46.791)	(0.006)

Table 9. (Continued).

Subj	Cond	Cont	Max	Tmax	Min	Tmin	ROM	ContVel	MaxVel	TmaxVel
5	1	-8.764	24.642	0.213	-8.764	0.000	33.406	467.725	594.003	0.013
		(8.657)	(2.919)	(0.032)	(8.657)	(0.000)	(7.182)	(112.174)	(67.605)	(0.009)
	2	-9.854	25.915	0.163	-9.959	0.120	35.874	625.702	820.027	0.011
		(11.000)	(1.164)	(0.023)	(10.838)	(0.268)	(10.560)	(120.650)	(154.390)	(0.010)
	3	-14.157	24.518	0.170	-14.157	0.000	38.675	950.615	1142.011	0.009
		(9.626)	(1.553)	(0.057)	(9.626)	(0.000)	(9.499)	(198.185)	(103.702)	(0.009)
	4	-20.614	22.595	0.150	-20.614	0.000	43.209	986.265	1273.975	0.012
		(4.902)	(1.346)	(0.048)	(4.902)	(0.000)	(5.043)	(270.130)	(108.076)	(0.006)
	5	-12.107	19.237	0.154	-14.591	0.118	33.828	611.887	718.862	0.010
		(11.560)	(1.157)	(0.055)	(7.108)	(0.265)	(7.045)	(105.337)	(96.693)	(0.010)
	6	-10.612	20.540	0.136	-10.612	0.000	31.152	683.166	811.301	0.010
		(8.675)	(1.687)	(0.037)	(8.675)	(0.000)	(9.423)	(105.055)	(41.509)	(0.010)
	7	-8.992	20.871	0.157	-8.992	0.000	29.863	864.726	909.814	0.007
		(4.481)	(1.717)	(0.064)	(4.481)	(0.000)	(5.134)	(60.405)	(54.916)	(0.005)
	8	-14.867	21.406	0.188	-14.867	0.000	36.273	840.312	969.409	0.011
		(3.325)	(1.024)	(0.048)	(3.325)	(0.000)	(4.061)	(98.886)	(54.560)	(0.004)
6	1	-2.690	36.491	0.248	-2.690	0.000	39.181	507.984	624.459	0.012
		(8.707)	(2.181)	(0.017)	(8.707)	(0.000)	(7.787)	(77.144)	(87.719)	(0.009)
	2	-0.449	39.818	0.238	-0.449	0.000	40.266	622.882	732.861	0.009
		(7.538)	(1.576)	(0.022)	(7.538)	(0.000)	(6.479)	(70.214)	(73.718)	(0.008)
	3	4.992	41.909	0.233	3.482	0.240	38.428	672.474	768.222	0.008
		(9.622)	(1.606)	(0.059)	(7.816)	(0.329)	(9.122)	(113.589)	(94.434)	(0.008)
	4	2.282	41.741	0.221	2.237	0.120	39.504	719.162	855.159	0.009
		(8.421)	(3.228)	(0.043)	(8.345)	(0.268)	(8.540)	(97.686)	(97.440)	(0.006)
	5	-9.608	32.390	0.249	-9.608	0.000	41.998	476.753	649.904	0.018
		(2.637)	(1.376)	(0.011)	(2.637)	(0.000)	(3.660)	(103.688)	(29.288)	(0.006)
	6	-9.841	36.388	0.258	-9.841	0.000	46.229	633.126	826.227	0.014
		(4.522)	(3.427)	(0.048)	(4.522)	(0.000)	(2.797)	(125.229)	(72.644)	(0.005)
	7	-8.038	39.765	0.252	-8.038	0.000	47.803	691.900	924.892	0.014
		(5.434)	(2.315)	(0.038)	(5.434)	(0.000)	(6.950)	(199.362)	(76.478)	(0.009)
	8	-6.659	40.211	0.269	-6.659	0.000	46.870	756.699	932.015	0.013
		(3.584)	(1.456)	(0.023)	(3.584)	(0.000)	(4.196)	(144.880)	(69.257)	(0.005)

Table 9. (Continued).

Subj	Cond	Cont	Max	Tmax	Min	Tmin	ROM	ContVel	MaxVel	TmaxVel
7	1	-31.399	21.073	0.203	-31.399	0.000	52.471	468.261	934.322	0.023
		(8.371)	(4.196)	(0.087)	(8.371)	(0.000)	(11.843)	(263.881)	(66.596)	(0.012)
	2	-31.738	26.267	0.265	-31.738	0.000	58.005	647.831	991.332	0.022
		(1.876)	(2.876)	(0.060)	(1.876)	(0.000)	(4.116)	(128.428)	(54.582)	(0.003)
	3	-29.702	25.003	0.311	-29.702	0.000	54.706	684.122	1070.717	0.018
		(8.650)	(1.738)	(0.061)	(8.650)	(0.000)	(8.796)	(244.455)	(76.073)	(0.010)
	4	-22.901	23.905	0.234	-22.901	0.000	46.806	1019.425	1202.247	0.010
		(8.611)	(2.334)	(0.034)	(8.611)	(0.000)	(7.918)	(130.568)	(94.061)	(0.007)
	5	-35.250	23.770	0.310	-35.250	0.000	59.021	342.241	771.031	0.034
		(4.211)	(1.118)	(0.093)	(4.211)	(0.000)	(3.608)	(127.584)	(70.658)	(0.008)
	6	-31.478	24.682	0.248	-31.478	0.000	56.160	463.529	926.376	0.028
		(3.074)	(1.721)	(0.033)	(3.074)	(0.000)	(2.742)	(158.537)	(56.213)	(0.008)
	7	-30.363	20.866	0.179	-30.363	0.000	51.228	537.319	987.743	0.025
		(6.202)	(3.734)	(0.099)	(6.202)	(0.000)	(6.461)	(114.882)	(54.729)	(0.003)
	8	-27.817	19.936	0.233	-27.817	0.000	47.753	705.174	1064.637	0.019
		(6.479)	(4.321)	(0.113)	(6.479)	(0.000)	(5.773)	(263.055)	(69.750)	(0.008)
8	1	-21.251	23.363	0.356	-21.251	0.000	44.613	543.391	789.380	0.017
		(6.323)	(1.266)	(0.118)	(6.323)	(0.000)	(6.824)	(191.923)	(77.620)	(0.010)
	2	-26.169	23.298	0.331	-26.169	0.000	49.467	605.652	1036.727	0.020
		(2.670)	(2.278)	(0.130)	(2.670)	(0.000)	(4.821)	(195.936)	(46.629)	(0.007)
	3	-24.196	22.626	0.297	-24.196	0.000	46.822	797.179	1141.000	0.015
		(3.739)	(1.440)	(0.123)	(3.739)	(0.000)	(4.573)	(185.562)	(119.335)	(0.006)
	4	-27.564	22.360	0.315	-27.564	0.000	49.923	657.460	1193.254	0.019
		(3.896)	(0.953)	(0.158)	(3.896)	(0.000)	(3.300)	(150.514)	(16.362)	(0.005)
	5	-31.045	18.281	0.394	-31.045	0.000	49.326	503.249	892.443	0.024
		(4.673)	(1.226)	(0.104)	(4.673)	(0.000)	(4.757)	(87.474)	(59.051)	(0.004)
	6	-29.365	15.575	0.398	-29.365	0.000	44.940	627.796	974.729	0.019
		(2.742)	(1.992)	(0.109)	(2.742)	(0.000)	(2.670)	(74.317)	(91.483)	(0.002)
	7	-26.840	15.453	0.362	-26.840	0.000	42.294	705.974	985.538	0.018
		(4.929)	(0.993)	(0.192)	(4.929)	(0.000)	(4.982)	(150.759)	(57.389)	(0.006)
	8	-29.756	15.903	0.214	-29.756	0.000	45.659	602.534	1098.591	0.023
		(4.102)	(2.356)	(0.141)	(4.102)	(0.000)	(4.576)	(168.648)	(40.423)	(0.005)

Table 9. (Continued).

Subj	Cond	Cont	Max	Tmax	Min	Tmin	ROM	ContVel	MaxVel	TmaxVel
9	1	0.516	17.909	0.166	-4.786	0.301	22.694	221.352	296.488	0.021
		(9.168)	(1.109)	(0.029)	(3.344)	(0.277)	(4.125)	(97.885)	(161.249)	(0.027)
	2	-19.016	16.580	0.169	-19.016	0.000	35.596	626.380	833.704	0.014
		(3.748)	(1.486)	(0.005)	(3.748)	(0.000)	(3.311)	(186.997)	(68.770)	(0.007)
	3	-17.259	17.854	0.159	-17.259	0.000	35.113	802.352	963.577	0.010
		(4.100)	(2.231)	(0.015)	(4.100)	(0.000)	(5.415)	(139.033)	(51.272)	(0.007)
	4	-17.356	17.612	0.159	-17.356	0.000	34.968	841.472	1076.706	0.010
		(11.169)	(3.873)	(0.022)	(11.169)	(0.000)	(9.049)	(283.088)	(85.170)	(0.010)
	5	-15.705	17.076	0.185	-16.577	0.112	33.653	470.571	624.141	0.013
		(11.061)	(1.444)	(0.025)	(9.139)	(0.250)	(9.493)	(97.161)	(126.558)	(0.009)
	6	-21.879	17.183	0.163	-21.879	0.000	39.063	555.285	816.241	0.018
		(4.436)	(0.964)	(0.014)	(4.436)	(0.000)	(4.324)	(91.430)	(83.613)	(0.006)
	7	-18.033	19.112	0.183	-18.033	0.000	37.144	723.740	937.654	0.012
		(8.870)	(0.956)	(0.021)	(8.870)	(0.000)	(9.351)	(198.514)	(47.743)	(0.010)
	8	-13.163	19.126	0.160	-16.426	0.233	35.552	744.214	938.301	0.010
		(14.528)	(1.357)	(0.013)	(9.361)	(0.320)	(9.774)	(130.779)	(132.658)	(0.010)
10	1	-16.116	20.212	0.128	-16.116	0.000	36.328	511.262	632.592	0.019
		(2.111)	(1.127)	(0.010)	(2.111)	(0.000)	(2.262)	(64.584)	(16.337)	(0.005)
	2	-19.003	24.740	0.118	-19.003	0.000	43.743	512.452	740.035	0.023
		(4.215)	(1.480)	(0.020)	(4.215)	(0.000)	(3.680)	(90.453)	(44.128)	(0.008)
	3	-18.312	24.727	0.149	-18.312	0.000	43.039	623.312	831.688	0.020
		(2.544)	(1.373)	(0.036)	(2.544)	(0.000)	(2.478)	(90.634)	(107.731)	(0.004)
	4	-17.412	26.523	0.164	-17.412	0.000	43.935	625.136	807.077	0.019
		(3.888)	(0.767)	(0.018)	(3.888)	(0.000)	(3.908)	(79.320)	(28.140)	(0.005)
	5	-24.654	16.176	0.117	-24.654	0.000	40.830	441.937	642.009	0.027
		(2.447)	(1.570)	(0.007)	(2.447)	(0.000)	(3.706)	(80.232)	(32.252)	(0.007)
	6	-24.095	17.737	0.109	-24.095	0.000	41.832	470.209	699.486	0.027
		(3.925)	(1.397)	(0.028)	(3.925)	(0.000)	(4.178)	(37.760)	(44.982)	(0.004)
	7	-25.404	19.962	0.088	-25.404	0.000	45.366	539.756	802.093	0.026
		(3.238)	(0.707)	(0.007)	(3.238)	(0.000)	(3.562)	(54.402)	(36.788)	(0.003)
	8	-23.461	19.219	0.085	-23.461	0.000	42.681	554.390	797.501	0.025
		(3.560)	(1.934)	(0.007)	(3.560)	(0.000)	(2.777)	(116.390)	(54.068)	(0.005)

Note: Angle and ROM units are in degrees and time unit is in s.
Velocity unit is in deg/s.
Standard deviation values are in parenthesis.
The definitions of variables are in Appendix A.

Table 10. Subject means and standard deviations of ankle joint variables (Group 2).

Subj	Cond	Cont	Max	Tmax	Min	Tmin	ROM	ContVel	MaxVel	TmaxVel
1	1	-3.233	20.675	0.251	-4.390	0.237	25.064	65.341	276.904	0.038
		(3.827)	(3.815)	(0.019)	(3.327)	(0.324)	(1.959)	(54.541)	(52.666)	(0.005)
	2	-5.186	20.503	0.199	-5.796	0.226	26.299	255.486	375.850	0.021
		(3.424)	(1.363)	(0.028)	(3.129)	(0.309)	(2.042)	(123.380)	(52.067)	(0.011)
	3	-10.446	20.267	0.241	-10.446	0.000	30.713	369.661	474.626	0.016
		(3.135)	(4.098)	(0.049)	(3.135)	(0.000)	(4.956)	(67.846)	(17.677)	(0.007)
	4	-8.998	20.286	0.235	-8.998	0.000	29.284	342.121	468.932	0.018
		(3.831)	(0.549)	(0.068)	(3.831)	(0.000)	(3.864)	(136.347)	(54.533)	(0.010)
	5	-10.185	20.039	0.225	-11.971	0.091	32.010	424.936	499.502	0.013
		(3.049)	(0.609)	(0.030)	(6.419)	(0.203)	(6.524)	(119.493)	(47.779)	(0.010)
	6	-16.284	18.430	0.296	-16.284	0.000	34.714	503.948	607.194	0.013
		(5.512)	(1.674)	(0.049)	(5.512)	(0.000)	(5.339)	(99.678)	(16.875)	(0.009)
	7	-12.908	16.500	0.230	-12.908	0.000	29.407	664.699	700.626	0.008
		(3.161)	(0.774)	(0.053)	(3.161)	(0.000)	(3.766)	(51.025)	(27.583)	(0.005)
	8	-22.048	18.225	0.228	-22.048	0.000	40.273	568.742	751.651	0.017
		(5.953)	(5.266)	(0.084)	(5.953)	(0.000)	(4.185)	(114.602)	(27.617)	(0.010)
2	1	1.404	18.626	0.156	-0.815	0.360	19.441	53.254	224.522	0.032
		(0.579)	(1.111)	(0.032)	(4.063)	(0.329)	(3.594)	(55.666)	(22.433)	(0.006)
	2	2.478	22.748	0.150	1.906	0.120	20.842	221.257	290.877	0.054
		(2.839)	(1.552)	(0.041)	(2.595)	(0.268)	(3.403)	(70.453)	(69.517)	(0.035)
	3	-0.165	24.238	0.158	-0.165	0.000	24.403	409.575	448.445	0.018
		(5.810)	(0.704)	(0.043)	(5.810)	(0.000)	(5.721)	(145.035)	(179.305)	(0.032)
	4	0.874	26.717	0.131	-1.934	0.240	28.651	701.727	715.009	0.002
		(5.083)	(1.918)	(0.026)	(3.508)	(0.329)	(2.304)	(136.316)	(121.335)	(0.004)
	5	0.677	25.565	0.155	0.677	0.000	24.888	247.604	350.062	0.018
		(2.354)	(2.131)	(0.011)	(2.354)	(0.000)	(2.712)	(37.759)	(63.303)	(0.003)
	6	-6.681	23.562	0.147	-6.681	0.000	30.243	513.493	580.145	0.011
		(2.405)	(0.919)	(0.015)	(2.405)	(0.000)	(2.097)	(54.510)	(56.102)	(0.004)
	7	-18.945	24.502	0.135	-18.945	0.000	43.447	640.023	939.172	0.015
		(7.967)	(2.355)	(0.008)	(7.967)	(0.000)	(6.332)	(163.364)	(134.589)	(0.009)
	8	-18.251	23.436	0.149	-18.251	0.000	41.686	693.637	972.424	0.015
		(6.472)	(2.592)	(0.062)	(6.472)	(0.000)	(5.788)	(210.349)	(135.934)	(0.007)

Table 10. (Continued).

Subj	Cond	Cont	Max	Tmax	Min	Tmin	ROM	ContVel	MaxVel	TmaxVel
3	1	-4.161	20.221	0.252	-4.190	0.001	24.411	102.500	269.997	0.029
		(3.732)	(1.686)	(0.044)	(3.720)	(0.002)	(4.730)	(136.842)	(60.128)	(0.013)
	2	-1.249	21.505	0.231	-2.206	0.126	23.711	140.599	312.757	0.034
		(7.764)	(2.600)	(0.071)	(7.226)	(0.265)	(6.417)	(198.449)	(158.310)	(0.021)
	3	-6.254	20.181	0.247	-6.254	0.000	26.435	389.515	497.999	0.029
		(8.340)	(3.292)	(0.059)	(8.340)	(0.000)	(9.500)	(255.688)	(246.119)	(0.035)
	4	-15.381	20.169	0.222	-15.381	0.000	35.550	601.254	796.131	0.011
		(5.845)	(2.179)	(0.108)	(5.845)	(0.000)	(7.023)	(160.830)	(156.762)	(0.006)
	5	-11.408	18.539	0.204	-11.477	0.002	30.017	199.294	457.365	0.028
		(9.048)	(4.046)	(0.060)	(8.989)	(0.004)	(7.201)	(260.137)	(191.243)	(0.011)
	6	-10.260	23.089	0.276	-10.260	0.000	33.348	577.615	705.028	0.011
		(5.512)	(1.441)	(0.058)	(5.512)	(0.000)	(6.844)	(64.180)	(77.912)	(0.008)
	7	-10.889	23.946	0.145	-10.889	0.000	34.835	648.013	782.242	0.011
		(5.376)	(2.936)	(0.020)	(5.376)	(0.000)	(4.016)	(102.629)	(86.407)	(0.004)
	8	-6.964	23.808	0.157	-6.964	0.000	30.772	737.067	850.866	0.009
		(7.855)	(2.220)	(0.063)	(7.855)	(0.000)	(6.820)	(187.670)	(175.943)	(0.006)

Note: Angle and ROM units are in degrees and time unit is in s.
Velocity unit is in deg/s.
Standard deviation values are in parenthesis.
The definitions of variables are in Appendix A.

Table 11. Subject means and standard deviations of knee joint variables (Group 1).

Subj	Cond	Cont	Max	Tmax	Min	Tmin	ROM	ContVel	MaxVel	TmaxVel
1	1	18.391	81.511	0.192	12.267	0.600	69.245	248.794	651.977	0.067
		(3.493)	(4.671)	(0.016)	(5.456)	(0.000)	(3.050)	(93.326)	(59.959)	(0.013)
	2	28.624	92.493	0.192	21.120	0.480	71.373	425.865	685.800	0.043
		(3.366)	(4.922)	(0.008)	(7.493)	(0.268)	(3.727)	(97.807)	(48.004)	(0.009)
	3	19.782	96.393	0.207	18.787	0.240	77.606	262.198	881.855	0.060
		(4.284)	(4.303)	(0.009)	(4.956)	(0.329)	(4.854)	(107.966)	(46.717)	(0.015)
	4	30.480	104.573	0.209	28.925	0.360	75.648	485.215	941.848	0.039
		(6.549)	(4.057)	(0.020)	(5.897)	(0.329)	(7.122)	(174.125)	(57.883)	(0.013)
	5	20.117	71.286	0.143	12.391	0.360	58.895	286.684	634.761	0.057
		(4.224)	(1.535)	(0.005)	(5.327)	(0.329)	(6.494)	(90.852)	(78.551)	(0.012)
	6	19.321	79.940	0.158	8.595	0.600	71.345	336.240	785.069	0.048
		(2.689)	(3.551)	(0.018)	(3.377)	(0.000)	(2.137)	(100.864)	(82.600)	(0.007)
	7	29.703	95.615	0.183	18.218	0.600	77.397	508.608	783.159	0.034
		(5.328)	(3.358)	(0.014)	(4.267)	(0.000)	(3.362)	(110.731)	(40.443)	(0.009)
	8	25.239	99.369	0.176	19.849	0.360	79.520	399.844	866.009	0.048
		(3.524)	(4.457)	(0.020)	(4.708)	(0.329)	(3.481)	(78.632)	(107.371)	(0.013)
2	1	20.450	69.792	0.197	20.450	0.000	49.341	251.252	609.774	0.054
		(3.654)	(4.783)	(0.030)	(3.654)	(0.000)	(4.627)	(61.089)	(79.172)	(0.008)
	2	26.462	76.357	0.178	26.462	0.000	49.894	380.092	672.076	0.042
		(2.832)	(2.922)	(0.018)	(2.832)	(0.000)	(4.749)	(56.245)	(29.034)	(0.010)
	3	23.385	78.763	0.190	23.385	0.000	55.378	322.299	785.973	0.047
		(2.927)	(2.641)	(0.031)	(2.927)	(0.000)	(4.137)	(78.696)	(78.379)	(0.007)
	4	24.934	82.651	0.167	24.934	0.000	57.716	398.859	863.268	0.041
		(2.250)	(2.298)	(0.006)	(2.250)	(0.000)	(1.536)	(59.502)	(52.576)	(0.005)
	5	19.077	64.674	0.163	19.077	0.000	45.597	258.641	569.730	0.057
		(2.674)	(1.812)	(0.022)	(2.674)	(0.000)	(2.837)	(53.406)	(38.402)	(0.007)
	6	20.218	69.661	0.162	20.218	0.000	49.443	326.695	685.317	0.047
		(1.880)	(1.850)	(0.008)	(1.880)	(0.000)	(1.735)	(30.449)	(83.764)	(0.006)
	7	23.143	74.753	0.174	23.143	0.000	51.610	342.068	744.756	0.046
		(3.007)	(1.700)	(0.014)	(3.007)	(0.000)	(1.848)	(41.510)	(55.259)	(0.004)
	8	26.940	76.241	0.181	26.560	0.120	49.681	342.159	656.059	0.045
		(5.993)	(5.183)	(0.065)	(5.539)	(0.268)	(9.692)	(77.409)	(146.972)	(0.012)

Table 11. (Continued).

Subj	Cond	Cont	Max	Tmax	Min	Tmin	ROM	ContVel	MaxVel	TmaxVel
3	1	32.260	72.811	0.138	20.001	0.461	52.810	445.602	614.260	0.033
		(9.037)	(3.124)	(0.021)	(3.168)	(0.018)	(5.286)	(193.237)	(113.848)	(0.019)
	2	34.669	90.430	0.185	23.754	0.545	66.676	447.828	667.605	0.037
		(3.848)	(8.773)	(0.041)	(5.709)	(0.061)	(3.690)	(58.402)	(56.011)	(0.010)
	3	32.365	93.004	0.180	21.010	0.575	71.995	356.675	768.469	0.050
		(3.135)	(2.373)	(0.012)	(5.346)	(0.024)	(5.522)	(74.796)	(140.842)	(0.007)
	4	42.550	102.876	0.195	24.135	0.597	78.740	548.723	766.625	0.030
		(7.747)	(3.009)	(0.023)	(7.042)	(0.007)	(6.473)	(141.739)	(62.734)	(0.017)
	5	25.324	72.258	0.140	20.807	0.386	51.451	290.823	617.890	0.049
		(3.568)	(3.703)	(0.022)	(1.297)	(0.217)	(4.349)	(46.354)	(74.408)	(0.010)
	6	28.891	95.079	0.213	20.546	0.478	74.533	369.694	665.919	0.057
		(2.416)	(4.637)	(0.025)	(6.876)	(0.267)	(4.086)	(30.494)	(113.845)	(0.007)
	7	35.107	100.227	0.205	20.968	0.596	79.259	438.168	704.703	0.045
		(6.180)	(4.792)	(0.013)	(4.191)	(0.007)	(2.197)	(100.645)	(59.823)	(0.015)
	8	36.887	102.532	0.188	23.803	0.599	78.729	463.822	802.096	0.039
		(7.110)	(7.265)	(0.018)	(3.615)	(0.002)	(7.810)	(165.196)	(125.388)	(0.017)
4	1	41.584	96.094	0.240	39.217	0.240	56.877	318.295	625.658	0.038
		(5.428)	(3.972)	(0.026)	(4.124)	(0.329)	(2.677)	(114.160)	(52.686)	(0.014)
	2	42.609	100.333	0.218	41.125	0.120	59.208	312.203	686.589	0.037
		(2.280)	(2.923)	(0.018)	(2.005)	(0.268)	(2.904)	(79.508)	(37.927)	(0.007)
	3	38.506	99.613	0.224	38.506	0.000	61.107	277.902	793.516	0.039
		(1.124)	(2.986)	(0.015)	(1.124)	(0.000)	(2.968)	(94.731)	(55.483)	(0.007)
	4	34.604	99.374	0.232	34.604	0.000	64.771	286.583	885.643	0.041
		(2.809)	(2.203)	(0.017)	(2.809)	(0.000)	(3.240)	(181.155)	(108.572)	(0.010)
	5	41.311	88.785	0.199	34.318	0.120	54.466	379.211	588.126	0.034
		(10.967)	(5.933)	(0.025)	(6.099)	(0.268)	(8.494)	(129.404)	(8.423)	(0.020)
	6	35.577	91.037	0.192	33.262	0.240	57.776	260.308	702.241	0.043
		(2.224)	(1.516)	(0.003)	(3.173)	(0.329)	(4.497)	(80.975)	(41.557)	(0.007)
	7	34.544	97.332	0.221	34.544	0.000	62.788	244.948	796.247	0.046
		(2.767)	(3.278)	(0.028)	(2.767)	(0.000)	(3.876)	(51.111)	(47.346)	(0.006)
	8	33.028	99.760	0.215	33.028	0.000	66.732	313.054	798.200	0.046
		(1.673)	(3.154)	(0.023)	(1.673)	(0.000)	(3.833)	(86.686)	(36.315)	(0.003)

Table 11. (Continued).

Subj	Cond	Cont	Max	Tmax	Min	Tmin	ROM	ContVel	MaxVel	TmaxVel
5	1	35.055	88.269	0.203	35.029	0.120	53.240	407.737	603.362	0.035
		(8.328)	(11.693)	(0.040)	(8.335)	(0.268)	(7.846)	(83.855)	(29.981)	(0.014)
	2	40.486	95.187	0.201	37.525	0.120	57.662	450.771	691.166	0.037
		(6.186)	(6.806)	(0.025)	(6.835)	(0.268)	(5.339)	(121.100)	(71.186)	(0.016)
	3	41.823	101.863	0.197	37.397	0.360	64.466	507.022	675.525	0.042
		(5.620)	(2.817)	(0.011)	(6.473)	(0.329)	(6.354)	(105.272)	(52.581)	(0.011)
	4	38.503	93.196	0.165	27.069	0.500	66.128	442.668	724.920	0.041
		(4.415)	(5.947)	(0.028)	(11.464)	(0.245)	(9.907)	(68.832)	(135.914)	(0.004)
	5	34.938	78.754	0.162	22.894	0.479	55.859	418.340	528.148	0.038
		(7.435)	(3.230)	(0.029)	(11.055)	(0.268)	(11.581)	(66.412)	(43.910)	(0.016)
	6	36.479	88.167	0.175	26.208	0.360	61.959	465.651	637.470	0.034
		(4.727)	(6.005)	(0.029)	(7.517)	(0.329)	(9.453)	(104.009)	(45.763)	(0.014)
	7	38.022	93.515	0.169	17.912	0.600	75.603	495.444	726.717	0.030
		(3.038)	(6.480)	(0.016)	(7.265)	(0.000)	(2.858)	(62.184)	(55.017)	(0.006)
	8	39.828	96.891	0.173	16.949	0.600	79.943	404.661	700.100	0.037
		(2.838)	(5.172)	(0.013)	(2.656)	(0.000)	(3.506)	(49.876)	(24.970)	(0.005)
6	1	37.275	97.553	0.237	30.310	0.360	67.243	331.363	676.304	0.037
		(7.018)	(2.710)	(0.012)	(8.626)	(0.329)	(8.396)	(78.866)	(42.877)	(0.012)
	2	40.640	104.436	0.228	39.418	0.240	65.018	413.049	720.687	0.034
		(4.489)	(3.108)	(0.012)	(3.051)	(0.329)	(2.113)	(120.393)	(37.300)	(0.010)
	3	43.235	108.932	0.232	37.360	0.240	71.571	510.144	834.586	0.028
		(6.279)	(5.037)	(0.037)	(7.284)	(0.329)	(5.413)	(188.201)	(30.471)	(0.013)
	4	41.665	111.658	0.231	38.357	0.360	73.302	409.812	880.947	0.032
		(5.481)	(5.376)	(0.022)	(3.461)	(0.329)	(4.905)	(156.394)	(104.468)	(0.010)
	5	32.396	92.079	0.225	27.608	0.480	64.471	278.578	650.994	0.043
		(2.679)	(3.492)	(0.013)	(6.104)	(0.268)	(2.847)	(53.400)	(51.106)	(0.008)
	6	37.325	101.738	0.245	37.325	0.000	64.413	386.597	627.662	0.040
		(2.534)	(5.059)	(0.022)	(2.534)	(0.000)	(5.815)	(53.457)	(40.821)	(0.008)
	7	39.527	109.475	0.262	39.527	0.000	69.948	406.803	680.469	0.042
		(4.133)	(2.386)	(0.021)	(4.133)	(0.000)	(5.893)	(53.985)	(35.179)	(0.008)
	8	38.620	113.564	0.248	38.620	0.000	74.945	432.375	800.514	0.040
		(2.807)	(3.029)	(0.016)	(2.807)	(0.000)	(4.632)	(30.254)	(48.260)	(0.005)

Table 11. (Continued).

Subj	Cond	Cont	Max	Tmax	Min	Tmin	ROM	ContVel	MaxVel	TmaxVel
7	1	27.319	81.088	0.200	20.119	0.360	60.970	273.268	481.812	0.067
		(4.537)	(11.627)	(0.060)	(7.154)	(0.329)	(5.922)	(88.498)	(52.801)	(0.024)
	2	32.908	98.851	0.246	32.908	0.000	65.943	451.349	555.490	0.020
		(5.345)	(9.467)	(0.032)	(5.345)	(0.000)	(6.590)	(46.641)	(63.781)	(0.004)
	3	35.503	107.270	0.262	35.503	0.000	71.767	450.167	655.089	0.039
		(8.503)	(6.129)	(0.028)	(8.503)	(0.000)	(5.970)	(140.280)	(41.661)	(0.024)
	4	36.417	111.214	0.261	36.417	0.000	74.797	582.229	730.659	0.029
		(5.232)	(3.443)	(0.011)	(5.232)	(0.000)	(6.981)	(93.013)	(99.937)	(0.028)
	5	23.087	88.159	0.259	21.729	0.120	66.430	276.256	468.031	0.054
		(6.087)	(7.027)	(0.055)	(7.146)	(0.268)	(7.931)	(56.640)	(27.444)	(0.026)
	6	24.411	92.555	0.223	23.905	0.240	68.649	359.756	588.084	0.052
		(3.221)	(5.037)	(0.022)	(2.841)	(0.329)	(5.523)	(48.146)	(22.486)	(0.019)
	7	30.094	113.509	0.298	30.094	0.000	83.415	446.464	638.920	0.055
		(4.685)	(8.761)	(0.023)	(4.685)	(0.000)	(5.033)	(38.729)	(40.446)	(0.025)
	8	33.034	117.545	0.283	33.034	0.000	84.511	505.441	723.686	0.041
		(3.481)	(5.958)	(0.024)	(3.481)	(0.000)	(7.994)	(82.339)	(115.025)	(0.014)
8	1	21.374	85.627	0.384	21.374	0.000	64.253	322.903	641.877	0.048
		(3.397)	(7.945)	(0.128)	(3.397)	(0.000)	(7.854)	(29.765)	(32.844)	(0.008)
	2	25.244	103.106	0.336	25.244	0.000	77.862	360.460	689.507	0.056
		(2.543)	(9.938)	(0.069)	(2.543)	(0.000)	(11.985)	(50.828)	(24.669)	(0.009)
	3	25.797	101.356	0.282	25.797	0.000	75.559	398.587	838.450	0.049
		(1.201)	(8.854)	(0.085)	(1.201)	(0.000)	(8.968)	(80.714)	(110.591)	(0.006)
	4	24.410	102.883	0.309	24.410	0.000	78.473	338.331	845.843	0.054
		(2.367)	(4.991)	(0.081)	(2.367)	(0.000)	(6.123)	(26.998)	(59.215)	(0.004)
	5	19.611	91.560	0.323	19.611	0.000	71.949	351.379	606.074	0.052
		(1.637)	(4.160)	(0.062)	(1.637)	(0.000)	(3.416)	(28.918)	(82.770)	(0.010)
	6	24.704	100.202	0.282	24.704	0.000	75.498	414.317	715.485	0.052
		(1.025)	(4.961)	(0.040)	(1.025)	(0.000)	(4.249)	(47.232)	(84.607)	(0.006)
	7	27.249	100.106	0.247	27.249	0.000	72.857	476.554	723.964	0.044
		(2.806)	(2.700)	(0.036)	(2.806)	(0.000)	(3.935)	(53.006)	(26.120)	(0.008)
	8	26.406	100.708	0.243	26.406	0.000	74.301	450.251	772.890	0.058
		(1.568)	(2.206)	(0.032)	(1.568)	(0.000)	(3.356)	(38.439)	(77.425)	(0.014)

Table 11. (Continued).

Subj	Cond	Cont	Max	Tmax	Min	Tmin	ROM	ContVel	MaxVel	TmaxVel
9	1	36.434	76.652	0.141	12.385	0.538	64.267	401.998	713.104	0.024
		(15.398)	(2.403)	(0.030)	(6.466)	(0.023)	(7.222)	(247.106)	(40.946)	(0.022)
	2	23.837	74.111	0.145	5.581	0.546	68.529	272.979	720.542	0.044
		(3.205)	(3.013)	(0.009)	(5.572)	(0.027)	(5.313)	(97.056)	(26.592)	(0.006)
	3	27.206	80.174	0.141	9.501	0.549	70.673	385.388	862.942	0.039
		(1.027)	(3.669)	(0.020)	(7.864)	(0.033)	(11.043)	(150.688)	(115.351)	(0.009)
	4	26.994	80.500	0.128	7.908	0.544	72.592	420.064	864.912	0.037
		(6.055)	(3.848)	(0.030)	(7.671)	(0.035)	(5.695)	(170.640)	(38.658)	(0.013)
	5	31.395	80.507	0.173	19.553	0.477	60.954	354.453	616.594	0.036
		(8.314)	(1.825)	(0.024)	(4.522)	(0.267)	(5.930)	(153.145)	(31.968)	(0.018)
	6	28.270	78.243	0.157	14.828	0.472	63.415	328.715	665.984	0.044
		(2.451)	(2.305)	(0.007)	(9.070)	(0.264)	(10.609)	(65.739)	(78.642)	(0.005)
	7	30.619	82.680	0.152	10.830	0.564	71.850	428.749	686.340	0.039
		(5.619)	(4.326)	(0.015)	(7.878)	(0.056)	(11.603)	(125.075)	(94.923)	(0.013)
	8	34.748	86.136	0.136	10.803	0.591	75.333	532.746	790.841	0.031
		(8.502)	(2.757)	(0.019)	(7.944)	(0.021)	(9.633)	(167.870)	(39.778)	(0.016)
10	1	26.012	68.089	0.120	9.456	0.563	58.633	326.827	508.970	0.044
		(1.766)	(1.358)	(0.004)	(2.323)	(0.040)	(2.052)	(56.095)	(30.315)	(0.007)
	2	27.740	75.661	0.143	14.870	0.600	60.791	341.802	529.628	0.047
		(2.064)	(4.499)	(0.016)	(2.549)	(0.000)	(3.660)	(60.064)	(18.488)	(0.012)
	3	28.418	80.395	0.127	17.524	0.588	62.871	360.287	625.797	0.048
		(3.588)	(2.710)	(0.005)	(2.042)	(0.026)	(3.477)	(41.297)	(64.976)	(0.004)
	4	30.049	89.008	0.168	23.659	0.360	65.349	440.177	641.177	0.048
		(2.774)	(2.691)	(0.024)	(7.620)	(0.329)	(5.663)	(25.914)	(29.143)	(0.005)
	5	22.270	62.452	0.118	9.448	0.545	53.004	317.997	475.834	0.046
		(1.387)	(1.872)	(0.011)	(2.220)	(0.076)	(3.535)	(46.580)	(40.097)	(0.010)
	6	25.123	71.229	0.122	11.437	0.540	59.792	324.723	540.035	0.050
		(3.080)	(2.236)	(0.008)	(1.727)	(0.085)	(2.684)	(32.841)	(61.530)	(0.008)
	7	26.817	80.676	0.134	14.306	0.597	66.370	396.745	569.644	0.052
		(1.700)	(1.798)	(0.006)	(3.657)	(0.008)	(5.023)	(40.895)	(19.549)	(0.006)
	8	28.705	83.857	0.142	14.542	0.600	69.315	425.395	600.279	0.048
		(2.713)	(1.157)	(0.013)	(2.813)	(0.000)	(2.794)	(36.686)	(10.504)	(0.011)

Note: Angle and ROM units are in degrees and time unit is in s.
Velocity unit is in deg/s.
Standard deviation values are in parenthesis.
The definitions of variables are in Appendix A.

Table 12. Subject means and standard deviations of knee joint variables (Group 2).

Subj	Cond	Cont	Max	Tmax	Min	Tmin	ROM	ContVel	MaxVel	TmaxVel
1	1	26.626	82.613	0.207	8.991	0.599	73.622	290.447	600.116	0.048
		(4.718)	(5.590)	(0.011)	(3.960)	(0.002)	(2.078)	(43.996)	(19.795)	(0.008)
	2	30.396	84.431	0.186	10.504	0.595	73.927	370.154	647.645	0.039
		(5.264)	(1.638)	(0.027)	(8.364)	(0.011)	(8.035)	(51.695)	(51.014)	(0.009)
	3	31.329	86.945	0.188	11.453	0.599	75.492	404.171	685.845	0.035
		(4.170)	(7.633)	(0.034)	(4.374)	(0.002)	(3.405)	(94.297)	(31.011)	(0.009)
	4	32.517	90.142	0.202	13.263	0.600	76.879	383.773	692.780	0.037
		(4.655)	(2.387)	(0.009)	(5.789)	(0.000)	(4.450)	(82.731)	(38.363)	(0.009)
	5	32.153	79.856	0.172	8.204	0.568	71.652	393.660	565.341	0.035
		(4.517)	(3.261)	(0.013)	(2.735)	(0.028)	(2.434)	(65.386)	(25.522)	(0.009)
	6	29.396	82.438	0.213	9.580	0.598	72.859	391.494	596.918	0.036
		(5.234)	(4.693)	(0.026)	(8.494)	(0.004)	(6.721)	(45.001)	(31.744)	(0.005)
	7	34.729	84.056	0.159	11.334	0.595	72.722	466.637	618.304	0.028
		(3.990)	(3.421)	(0.024)	(3.104)	(0.005)	(6.277)	(41.153)	(28.460)	(0.004)
	8	30.294	82.967	0.156	11.614	0.585	71.353	424.749	635.179	0.037
		(3.761)	(8.940)	(0.028)	(5.969)	(0.016)	(13.402)	(78.040)	(62.785)	(0.009)
2	1	27.920	73.408	0.142	20.965	0.360	52.443	396.488	757.030	0.029
		(2.680)	(2.518)	(0.011)	(7.847)	(0.329)	(6.681)	(132.575)	(38.639)	(0.008)
	2	30.102	80.930	0.158	28.515	0.360	52.415	401.773	879.926	0.029
		(4.313)	(2.469)	(0.013)	(4.410)	(0.329)	(5.702)	(177.420)	(135.065)	(0.007)
	3	30.245	85.297	0.161	30.245	0.000	55.052	448.194	887.314	0.031
		(2.844)	(3.048)	(0.005)	(2.844)	(0.000)	(1.364)	(125.867)	(20.184)	(0.007)
	4	32.556	89.677	0.158	23.396	0.360	66.280	577.185	1125.636	0.025
		(6.522)	(3.529)	(0.012)	(8.228)	(0.329)	(5.085)	(218.382)	(132.436)	(0.007)
	5	30.330	79.554	0.148	27.223	0.120	52.331	500.213	725.268	0.023
		(1.902)	(2.467)	(0.007)	(8.146)	(0.268)	(7.281)	(96.248)	(27.460)	(0.006)
	6	28.375	78.544	0.148	27.555	0.120	50.989	401.514	753.332	0.031
		(1.340)	(2.703)	(0.009)	(2.498)	(0.268)	(2.153)	(63.954)	(57.746)	(0.005)
	7	24.709	81.515	0.169	24.709	0.000	56.806	341.009	878.317	0.041
		(3.480)	(3.353)	(0.014)	(3.480)	(0.000)	(3.093)	(94.206)	(121.100)	(0.008)
	8	25.384	86.163	0.162	23.267	0.360	62.896	379.099	943.781	0.040
		(4.832)	(4.479)	(0.006)	(5.360)	(0.329)	(2.254)	(85.913)	(74.933)	(0.007)

Table 12. (Continued).

Subj	Cond	Cont	Max	Tmax	Min	Tmin	ROM	ContVel	MaxVel	TmaxVel
3	1	27.772	80.003	0.220	27.772	0.000	52.231	286.030	637.149	0.033
		(4.417)	(8.028)	(0.029)	(4.417)	(0.000)	(4.037)	(67.656)	(40.376)	(0.007)
	2	32.897	93.043	0.264	30.400	0.240	62.644	357.039	763.341	0.030
		(5.187)	(6.472)	(0.042)	(4.492)	(0.329)	(4.446)	(116.161)	(65.280)	(0.006)
	3	33.061	95.099	0.249	33.061	0.000	62.037	353.942	808.088	0.034
		(5.248)	(3.442)	(0.019)	(5.248)	(0.000)	(6.467)	(138.572)	(54.878)	(0.009)
	4	30.835	102.097	0.288	30.835	0.000	71.262	273.293	895.241	0.040
		(2.798)	(2.659)	(0.043)	(2.798)	(0.000)	(4.578)	(58.036)	(54.168)	(0.006)
	5	21.123	66.712	0.203	21.123	0.000	45.589	278.076	607.630	0.038
		(5.365)	(12.683)	(0.040)	(5.365)	(0.000)	(7.914)	(104.934)	(70.824)	(0.014)
	6	31.809	91.123	0.267	31.809	0.000	59.314	364.334	709.675	0.035
		(3.757)	(4.898)	(0.033)	(3.757)	(0.000)	(5.810)	(142.502)	(34.444)	(0.012)
	7	34.724	90.258	0.228	34.710	0.120	55.549	321.884	678.267	0.037
		(3.534)	(3.958)	(0.057)	(3.520)	(0.268)	(2.731)	(79.774)	(35.814)	(0.006)
	8	35.887	97.669	0.228	35.887	0.000	61.782	483.054	748.563	0.031
		(4.275)	(5.594)	(0.053)	(4.275)	(0.000)	(9.548)	(103.643)	(46.125)	(0.010)

Note: Angle and ROM units are in degrees and time unit is in s.
Velocity unit is in deg/s.
Standard deviation values are in parenthesis.
The definitions of variables are in Appendix A.

Table 13. Subject means and standard deviations of hip joint variables (Group 1).

Subj	Cond	Cont	Max	Tmax	Min	Tmin	ROM	ContVel	MaxVel	TmaxVel
1	1	19.018	55.194	0.195	11.511	0.600	43.684	113.611	384.047	0.071
		(3.343)	(6.488)	(0.015)	(4.467)	(0.000)	(2.861)	(27.888)	(51.135)	(0.012)
	2	26.825	65.719	0.193	19.441	0.600	46.278	240.927	417.453	0.045
		(1.170)	(5.066)	(0.013)	(7.456)	(0.000)	(6.506)	(62.577)	(29.780)	(0.010)
	3	19.136	67.100	0.210	17.330	0.360	49.771	119.028	549.531	0.064
		(4.571)	(6.107)	(0.009)	(5.306)	(0.329)	(2.951)	(51.181)	(22.815)	(0.008)
	4	25.389	84.231	0.258	25.282	0.120	58.948	223.257	643.214	0.045
		(2.936)	(3.986)	(0.028)	(2.925)	(0.268)	(6.411)	(117.326)	(37.501)	(0.012)
	5	16.178	42.947	0.139	10.475	0.480	32.472	102.235	376.795	0.062
		(2.836)	(1.919)	(0.027)	(3.736)	(0.268)	(4.215)	(51.111)	(45.015)	(0.012)
	6	17.186	57.564	0.171	8.073	0.600	49.491	176.533	511.322	0.052
		(1.534)	(6.166)	(0.020)	(4.562)	(0.000)	(3.144)	(48.791)	(31.807)	(0.006)
	7	24.027	70.403	0.198	18.471	0.600	51.932	231.784	523.673	0.042
		(3.968)	(1.791)	(0.015)	(1.338)	(0.000)	(2.487)	(75.181)	(36.900)	(0.009)
	8	20.703	78.908	0.247	19.706	0.240	59.202	187.773	584.934	0.055
		(1.380)	(4.361)	(0.032)	(1.656)	(0.329)	(3.455)	(46.229)	(75.299)	(0.017)
2	1	31.792	73.988	0.273	31.792	0.000	42.196	93.595	452.127	0.060
		(3.610)	(6.931)	(0.056)	(3.610)	(0.000)	(6.058)	(42.601)	(22.101)	(0.006)
	2	36.589	81.523	0.263	36.589	0.000	44.935	155.943	482.425	0.052
		(5.535)	(5.592)	(0.052)	(5.535)	(0.000)	(5.388)	(44.304)	(28.153)	(0.008)
	3	37.414	100.123	0.277	37.414	0.000	62.709	157.865	661.321	0.054
		(2.042)	(5.643)	(0.021)	(2.042)	(0.000)	(6.476)	(51.558)	(33.867)	(0.009)
	4	37.107	101.145	0.265	37.107	0.000	64.037	207.409	677.999	0.047
		(2.929)	(6.014)	(0.013)	(2.929)	(0.000)	(4.230)	(36.087)	(44.481)	(0.005)
	5	33.262	71.811	0.265	33.262	0.000	38.549	55.783	433.632	0.066
		(4.632)	(7.846)	(0.032)	(4.632)	(0.000)	(4.456)	(44.947)	(51.506)	(0.008)
	6	36.316	88.530	0.266	36.316	0.000	52.214	138.168	552.153	0.056
		(1.210)	(6.271)	(0.021)	(1.210)	(0.000)	(6.019)	(30.003)	(68.485)	(0.006)
	7	36.503	94.636	0.258	36.503	0.000	58.132	141.958	612.886	0.053
		(1.845)	(7.764)	(0.022)	(1.845)	(0.000)	(7.701)	(23.183)	(37.792)	(0.005)
	8	43.481	106.786	0.255	43.481	0.000	63.306	202.930	671.995	0.056
		(4.269)	(4.764)	(0.030)	(4.269)	(0.000)	(3.809)	(48.631)	(63.873)	(0.010)

Table 13. (Continued).

Subj	Cond	Cont	Max	Tmax	Min	Tmin	ROM	ContVel	MaxVel	TmaxVel
3	1	39.092	61.019	0.143	25.467	0.586	35.552	165.812	352.051	0.039
		(5.046)	(3.649)	(0.020)	(1.795)	(0.034)	(4.858)	(147.455)	(59.216)	(0.021)
	2	39.741	72.879	0.190	29.010	0.595	43.869	146.287	385.708	0.044
		(3.885)	(11.050)	(0.041)	(6.353)	(0.011)	(4.712)	(31.593)	(61.117)	(0.011)
	3	38.836	80.345	0.201	28.769	0.586	51.576	107.844	519.557	0.058
		(1.998)	(5.087)	(0.029)	(5.462)	(0.017)	(4.345)	(46.022)	(70.931)	(0.012)
	4	46.161	97.532	0.212	32.807	0.498	64.725	263.024	575.613	0.039
		(5.973)	(6.741)	(0.035)	(8.379)	(0.244)	(4.116)	(116.176)	(53.487)	(0.019)
	5	35.729	59.269	0.140	27.169	0.554	32.100	58.054	342.412	0.053
		(1.934)	(3.080)	(0.022)	(0.999)	(0.065)	(3.273)	(32.233)	(33.746)	(0.008)
	6	42.508	90.254	0.225	29.748	0.480	60.507	142.297	466.733	0.066
		(2.621)	(8.816)	(0.036)	(9.597)	(0.268)	(4.687)	(21.459)	(55.656)	(0.010)
	7	46.171	96.845	0.217	30.872	0.600	65.973	203.123	503.397	0.054
		(2.498)	(4.345)	(0.013)	(4.961)	(0.000)	(3.849)	(67.702)	(32.449)	(0.015)
	8	41.055	100.782	0.230	36.453	0.480	64.329	243.203	587.970	0.048
		(6.738)	(4.355)	(0.014)	(3.524)	(0.268)	(3.264)	(119.149)	(90.194)	(0.016)
4	1	44.590	94.243	0.272	44.559	0.120	49.684	138.634	439.668	0.048
		(2.903)	(5.587)	(0.015)	(2.897)	(0.268)	(3.519)	(83.723)	(26.869)	(0.014)
	2	45.229	104.843	0.269	45.229	0.000	59.614	128.998	527.271	0.046
		(3.143)	(2.051)	(0.006)	(3.143)	(0.000)	(2.268)	(38.441)	(31.378)	(0.006)
	3	40.602	112.237	0.293	40.602	0.000	71.635	109.340	612.384	0.048
		(3.691)	(2.567)	(0.011)	(3.691)	(0.000)	(3.157)	(44.616)	(28.537)	(0.007)
	4	39.879	121.475	0.306	39.879	0.000	81.596	128.363	699.895	0.047
		(3.633)	(4.405)	(0.018)	(3.633)	(0.000)	(3.800)	(128.754)	(81.809)	(0.011)
	5	42.642	88.793	0.247	38.918	0.120	49.875	181.050	405.922	0.044
		(6.096)	(9.095)	(0.043)	(4.570)	(0.268)	(6.578)	(116.637)	(21.521)	(0.022)
	6	39.724	101.121	0.271	39.724	0.000	61.397	105.339	539.864	0.052
		(2.633)	(2.509)	(0.018)	(2.633)	(0.000)	(2.736)	(54.024)	(26.713)	(0.005)
	7	38.870	115.880	0.291	38.870	0.000	77.010	102.225	634.420	0.055
		(1.573)	(3.406)	(0.011)	(1.573)	(0.000)	(2.484)	(35.628)	(35.518)	(0.007)
	8	41.635	126.560	0.299	41.635	0.000	84.925	127.027	662.525	0.054
		(3.208)	(5.225)	(0.015)	(3.208)	(0.000)	(2.991)	(53.177)	(27.182)	(0.004)

Table 13. (Continued).

Subj	Cond	Cont	Max	Tmax	Min	Tmin	ROM	ContVel	MaxVel	TmaxVel
5	1	34.709	71.232	0.217	34.709	0.000	36.522	225.805	385.121	0.038
		(8.403)	(17.906)	(0.046)	(8.403)	(0.000)	(10.346)	(69.801)	(42.095)	(0.013)
	2	35.618	76.517	0.208	34.818	0.120	41.699	244.617	480.312	0.041
		(7.000)	(5.413)	(0.025)	(6.791)	(0.268)	(3.664)	(111.626)	(59.427)	(0.016)
	3	33.748	80.479	0.206	30.682	0.120	49.797	249.023	508.797	0.047
		(6.100)	(2.822)	(0.016)	(3.153)	(0.268)	(4.239)	(65.764)	(23.642)	(0.011)
	4	35.619	76.602	0.175	27.554	0.600	49.047	211.253	538.795	0.048
		(3.344)	(8.268)	(0.026)	(8.354)	(0.000)	(6.674)	(48.483)	(99.970)	(0.007)
	5	35.327	68.222	0.188	29.503	0.360	38.719	233.727	368.075	0.043
		(2.456)	(5.050)	(0.031)	(8.269)	(0.329)	(7.137)	(57.244)	(33.932)	(0.016)
	6	36.182	81.163	0.201	30.797	0.360	50.367	286.260	476.535	0.040
		(3.816)	(9.146)	(0.031)	(4.961)	(0.329)	(7.744)	(78.002)	(21.018)	(0.015)
	7	33.492	80.785	0.181	21.437	0.600	59.348	309.272	548.932	0.037
		(4.904)	(5.398)	(0.016)	(6.090)	(0.000)	(4.333)	(41.543)	(52.098)	(0.007)
	8	42.199	95.287	0.181	25.275	0.600	70.012	282.645	590.034	0.042
		(2.530)	(4.961)	(0.014)	(2.541)	(0.000)	(2.572)	(28.023)	(19.779)	(0.005)
6	1	42.382	84.845	0.252	40.884	0.240	43.961	135.231	428.782	0.044
		(4.095)	(5.129)	(0.021)	(6.524)	(0.329)	(6.822)	(45.621)	(39.729)	(0.012)
	2	43.987	94.753	0.254	43.987	0.000	50.766	169.371	467.925	0.043
		(3.048)	(2.418)	(0.024)	(3.048)	(0.000)	(3.899)	(78.998)	(25.139)	(0.011)
	3	43.360	98.349	0.248	40.949	0.120	57.401	257.163	563.733	0.035
		(4.450)	(7.012)	(0.038)	(4.644)	(0.268)	(6.868)	(110.396)	(35.037)	(0.012)
	4	41.882	104.191	0.249	41.171	0.120	63.019	205.460	641.516	0.039
		(2.160)	(5.969)	(0.015)	(0.943)	(0.268)	(5.622)	(98.691)	(51.011)	(0.007)
	5	36.816	83.193	0.258	34.300	0.240	48.893	117.849	423.609	0.050
		(2.957)	(5.671)	(0.014)	(5.227)	(0.329)	(1.031)	(42.236)	(39.968)	(0.009)
	6	42.558	99.458	0.281	42.558	0.000	56.900	157.603	433.789	0.052
		(1.419)	(5.274)	(0.015)	(1.419)	(0.000)	(6.540)	(26.134)	(31.937)	(0.007)
	7	41.737	108.396	0.292	41.737	0.000	66.659	206.298	516.240	0.052
		(3.429)	(3.742)	(0.019)	(3.429)	(0.000)	(5.246)	(48.197)	(41.428)	(0.010)
	8	37.687	117.782	0.273	37.687	0.000	80.095	236.354	636.454	0.048
		(2.978)	(4.069)	(0.011)	(2.978)	(0.000)	(6.622)	(38.237)	(54.790)	(0.005)

Table 13. (Continued).

Subj	Cond	Cont	Max	Tmax	Min	Tmin	ROM	ContVel	MaxVel	TmaxVel
7	1	29.672	64.205	0.241	27.536	0.240	36.670	40.052	324.887	0.078
		(3.277)	(13.723)	(0.031)	(4.667)	(0.329)	(9.661)	(38.245)	(55.973)	(0.017)
	2	31.102	74.804	0.268	31.102	0.000	43.703	148.931	335.227	0.087
		(3.044)	(8.410)	(0.015)	(3.044)	(0.000)	(6.012)	(35.716)	(13.267)	(0.016)
	3	38.231	100.225	0.269	38.231	0.000	61.994	196.462	485.190	0.073
		(2.452)	(2.848)	(0.018)	(2.452)	(0.000)	(4.447)	(46.322)	(103.377)	(0.009)
	4	37.391	111.971	0.290	37.391	0.000	74.579	235.721	548.151	0.063
		(4.086)	(2.802)	(0.009)	(4.086)	(0.000)	(5.150)	(37.796)	(84.478)	(0.009)
	5	29.273	71.560	0.275	26.305	0.120	45.256	80.709	305.520	0.080
		(2.550)	(10.898)	(0.051)	(6.039)	(0.268)	(12.096)	(36.008)	(19.804)	(0.016)
	6	29.480	78.885	0.269	29.480	0.000	49.406	110.662	397.962	0.074
		(4.377)	(8.258)	(0.027)	(4.377)	(0.000)	(5.104)	(40.243)	(51.519)	(0.010)
	7	32.323	104.354	0.310	32.323	0.000	72.032	208.919	476.978	0.083
		(5.770)	(4.061)	(0.015)	(5.770)	(0.000)	(3.444)	(24.866)	(32.861)	(0.015)
	8	37.426	117.574	0.292	37.426	0.000	80.149	232.406	589.337	0.071
		(4.518)	(11.237)	(0.020)	(4.518)	(0.000)	(11.401)	(56.948)	(97.146)	(0.014)
8	1	29.912	87.183	0.433	29.912	0.000	57.271	118.596	413.004	0.056
		(3.539)	(7.869)	(0.090)	(3.539)	(0.000)	(5.745)	(20.798)	(17.045)	(0.011)
	2	32.983	105.876	0.394	32.983	0.000	72.894	125.107	494.279	0.065
		(2.479)	(5.387)	(0.027)	(2.479)	(0.000)	(6.019)	(23.645)	(44.028)	(0.007)
	3	27.019	108.981	0.474	27.019	0.000	81.962	145.682	616.561	0.057
		(3.312)	(3.715)	(0.089)	(3.312)	(0.000)	(6.023)	(34.484)	(94.387)	(0.005)
	4	25.364	120.539	0.520	25.364	0.000	95.176	157.203	644.420	0.063
		(1.912)	(5.170)	(0.032)	(1.912)	(0.000)	(4.599)	(32.037)	(11.034)	(0.009)
	5	33.901	106.391	0.390	33.901	0.000	72.490	149.884	452.724	0.117
		(2.319)	(3.362)	(0.023)	(2.319)	(0.000)	(5.107)	(17.503)	(58.837)	(0.121)
	6	37.768	114.893	0.353	37.768	0.000	77.124	160.531	526.750	0.063
		(3.990)	(3.649)	(0.028)	(3.990)	(0.000)	(6.820)	(30.060)	(47.440)	(0.011)
	7	31.043	111.110	0.365	31.043	0.000	80.066	224.088	580.678	0.058
		(4.972)	(10.678)	(0.062)	(4.972)	(0.000)	(10.287)	(38.604)	(27.622)	(0.005)
	8	29.062	121.415	0.388	29.062	0.000	92.353	245.351	673.796	0.064
		(3.772)	(10.407)	(0.058)	(3.772)	(0.000)	(7.166)	(36.074)	(34.599)	(0.013)

Table 13. (Continued).

Subj	Cond	Cont	Max	Tmax	Min	Tmin	ROM	ContVel	MaxVel	TmaxVel
9	1	48.886	83.628	0.161	28.410	0.471	55.218	316.574	517.802	0.024
		(11.039)	(6.891)	(0.032)	(9.740)	(0.264)	(8.669)	(183.230)	(7.692)	(0.022)
	2	37.683	76.080	0.166	27.621	0.593	48.459	145.904	497.921	0.050
		(6.076)	(6.696)	(0.005)	(6.164)	(0.017)	(10.022)	(55.082)	(29.494)	(0.004)
	3	34.299	75.377	0.162	21.122	0.600	54.254	187.311	617.036	0.045
		(2.472)	(4.721)	(0.028)	(4.156)	(0.000)	(7.156)	(82.343)	(96.501)	(0.010)
	4	35.638	76.265	0.152	21.129	0.596	55.136	217.920	619.480	0.042
		(2.387)	(1.504)	(0.014)	(3.344)	(0.009)	(3.622)	(89.232)	(25.449)	(0.011)
	5	51.419	99.609	0.219	39.419	0.480	60.190	229.054	463.513	0.043
		(6.061)	(6.203)	(0.031)	(3.894)	(0.268)	(7.558)	(118.355)	(24.043)	(0.018)
	6	45.557	90.342	0.200	36.653	0.480	53.689	177.838	495.598	0.052
		(3.884)	(6.293)	(0.027)	(8.631)	(0.268)	(4.793)	(32.771)	(42.309)	(0.004)
	7	40.721	84.291	0.172	27.380	0.600	56.911	235.346	530.081	0.047
		(6.104)	(10.229)	(0.015)	(4.244)	(0.000)	(11.630)	(91.477)	(76.203)	(0.014)
	8	44.309	91.062	0.168	28.502	0.600	62.560	319.547	607.871	0.040
		(4.685)	(6.548)	(0.025)	(8.320)	(0.000)	(9.385)	(130.270)	(34.966)	(0.016)
10	1	32.090	55.043	0.134	24.111	0.600	30.932	112.664	276.996	0.059
		(1.778)	(4.334)	(0.008)	(3.377)	(0.000)	(5.978)	(37.132)	(40.218)	(0.006)
	2	30.760	56.911	0.159	17.885	0.600	39.026	97.794	292.088	0.065
		(4.004)	(5.653)	(0.017)	(3.207)	(0.000)	(3.156)	(30.666)	(21.156)	(0.010)
	3	28.608	60.609	0.143	18.614	0.600	41.995	145.587	383.931	0.056
		(2.851)	(3.685)	(0.021)	(3.014)	(0.000)	(2.871)	(32.275)	(37.201)	(0.002)
	4	34.207	77.104	0.210	29.723	0.480	47.381	199.952	429.297	0.059
		(2.058)	(4.662)	(0.025)	(6.047)	(0.268)	(2.551)	(15.650)	(15.957)	(0.006)
	5	29.723	51.017	0.133	20.002	0.585	31.015	97.021	253.519	0.064
		(2.868)	(4.959)	(0.021)	(4.071)	(0.034)	(4.529)	(33.001)	(10.416)	(0.014)
	6	25.528	51.599	0.130	14.060	0.600	37.540	129.234	304.457	0.058
		(2.223)	(6.364)	(0.010)	(2.365)	(0.000)	(4.452)	(42.264)	(51.559)	(0.006)
	7	27.654	62.512	0.159	17.219	0.600	45.293	146.223	363.156	0.069
		(3.755)	(5.439)	(0.014)	(1.291)	(0.000)	(4.790)	(26.244)	(21.789)	(0.008)
	8	27.145	68.768	0.178	20.192	0.600	48.576	215.687	412.300	0.062
		(2.731)	(5.206)	(0.025)	(2.126)	(0.000)	(6.178)	(24.935)	(13.046)	(0.006)

Note: Angle and ROM units are in degrees and time unit is in s.
Velocity unit is in deg/s.
Standard deviation values are in parenthesis.
The definitions of variables are in Appendix A.

Table 14. Subject means and standard deviations of hip joint variables (Group 2).

Subj	Cond	Cont	Max	Tmax	Min	Tmin	ROM	ContVel	MaxVel	TmaxVel
1	1	30.506	73.021	0.191	8.253	0.600	64.769	172.957	449.661	0.054
		(4.735)	(4.803)	(0.018)	(3.942)	(0.000)	(5.914)	(58.329)	(24.974)	(0.008)
	2	30.212	72.291	0.181	12.719	0.596	59.572	234.371	480.285	0.042
		(4.540)	(2.746)	(0.020)	(10.128)	(0.009)	(9.935)	(47.396)	(32.366)	(0.008)
	3	32.322	82.823	0.215	13.770	0.600	69.053	267.077	541.787	0.043
		(2.804)	(4.876)	(0.020)	(4.530)	(0.000)	(3.677)	(79.145)	(28.620)	(0.008)
	4	31.089	84.178	0.210	15.084	0.600	69.094	285.974	564.993	0.042
		(2.701)	(3.915)	(0.014)	(6.128)	(0.000)	(8.486)	(76.287)	(20.530)	(0.008)
	5	31.404	69.192	0.177	7.245	0.578	61.947	238.947	419.668	0.043
		(2.864)	(3.076)	(0.011)	(3.228)	(0.023)	(4.996)	(42.024)	(26.249)	(0.009)
	6	30.909	80.778	0.216	10.806	0.599	69.973	259.668	490.972	0.043
		(2.498)	(2.814)	(0.008)	(6.399)	(0.002)	(6.628)	(32.454)	(23.703)	(0.004)
	7	33.907	83.422	0.193	11.105	0.600	72.318	308.442	493.612	0.039
		(5.050)	(3.354)	(0.009)	(3.407)	(0.000)	(3.969)	(38.751)	(34.182)	(0.006)
	8	30.932	89.749	0.206	14.535	0.599	75.214	321.914	576.847	0.047
		(1.710)	(3.634)	(0.005)	(8.258)	(0.002)	(7.780)	(62.663)	(26.996)	(0.007)
2	1	32.281	57.844	0.148	28.714	0.359	29.131	205.131	460.015	0.031
		(4.442)	(3.705)	(0.026)	(4.084)	(0.328)	(2.033)	(118.708)	(36.982)	(0.010)
	2	32.396	67.866	0.188	32.396	0.000	35.471	203.229	550.390	0.034
		(1.844)	(3.246)	(0.011)	(1.844)	(0.000)	(3.375)	(102.967)	(57.336)	(0.006)
	3	32.456	75.351	0.193	32.456	0.000	42.894	233.200	592.972	0.035
		(1.769)	(2.921)	(0.008)	(1.769)	(0.000)	(2.575)	(103.544)	(23.858)	(0.007)
	4	34.190	84.313	0.196	34.101	0.120	50.211	326.710	739.745	0.028
		(1.703)	(5.350)	(0.035)	(1.778)	(0.268)	(6.322)	(139.517)	(92.109)	(0.008)
	5	33.192	59.943	0.150	29.919	0.240	30.024	267.327	423.369	0.026
		(2.869)	(4.621)	(0.024)	(5.611)	(0.329)	(8.052)	(97.631)	(42.213)	(0.008)
	6	31.702	70.642	0.191	30.769	0.120	39.874	171.090	461.632	0.036
		(1.134)	(9.043)	(0.028)	(1.441)	(0.268)	(8.484)	(47.440)	(53.290)	(0.005)
	7	32.716	82.719	0.224	32.716	0.000	50.002	111.667	578.328	0.047
		(3.627)	(10.350)	(0.022)	(3.627)	(0.000)	(8.472)	(63.192)	(108.084)	(0.009)
	8	32.787	90.405	0.201	32.787	0.000	57.619	148.541	677.570	0.046
		(3.120)	(6.074)	(0.021)	(3.120)	(0.000)	(3.482)	(68.071)	(53.819)	(0.007)

Table 14. (Continued).

Subj	Cond	Cont	Max	Tmax	Min	Tmin	ROM	ContVel	MaxVel	TmaxVel
3	1	25.475	62.955	0.234	25.475	0.000	37.480	213.160	446.945	0.035
		(4.961)	(12.990)	(0.043)	(4.961)	(0.000)	(8.179)	(60.199)	(38.535)	(0.007)
	2	30.816	87.384	0.268	30.600	0.240	56.784	264.241	589.015	0.033
		(1.890)	(8.527)	(0.036)	(1.738)	(0.329)	(8.165)	(121.494)	(29.824)	(0.009)
	3	35.064	109.710	0.304	35.064	0.000	74.646	236.247	674.542	0.041
		(3.238)	(2.206)	(0.017)	(3.238)	(0.000)	(2.894)	(113.872)	(28.659)	(0.008)
	4	32.429	129.211	0.338	32.429	0.000	96.782	229.616	749.451	0.044
		(2.571)	(3.718)	(0.025)	(2.571)	(0.000)	(5.089)	(50.795)	(27.111)	(0.005)
	5	24.506	60.086	0.224	24.506	0.000	35.580	156.773	448.068	0.042
		(3.785)	(11.270)	(0.039)	(3.785)	(0.000)	(8.740)	(107.965)	(52.746)	(0.015)
	6	36.456	114.331	0.323	36.456	0.000	77.876	237.734	591.653	0.041
		(5.193)	(4.298)	(0.025)	(5.193)	(0.000)	(7.814)	(116.662)	(48.636)	(0.012)
	7	35.724	118.676	0.293	35.724	0.000	82.952	218.277	608.543	0.043
		(5.979)	(1.840)	(0.011)	(5.979)	(0.000)	(5.140)	(42.259)	(17.280)	(0.004)
	8	39.684	137.730	0.332	39.684	0.000	98.046	344.366	699.641	0.041
		(6.735)	(7.368)	(0.046)	(6.735)	(0.000)	(5.772)	(77.210)	(42.666)	(0.009)

Note: Angle and ROM units are in degrees and time unit is in s.
Velocity unit is in deg/s.
Standard deviation values are in parenthesis.
The definitions of variables are in Appendix A.

APPENDIX D

VERTICAL GROUND REACTION FORCE DATA

Table 15. Subject means and standard deviations of VGRF variables (Group 1).

Subj	Cond	FI	T1	F2	T2	LrateF1	LrateF2	Imp100ms
1	1	14.100	0.009	53.537	0.051	1568.921	1343.100	2.691
		(2.600)	(0.002)	(8.404)	(0.008)	(175.864)	(447.434)	(0.311)
	2	20.014	0.008	63.453	0.041	2668.455	1953.229	2.810
		(1.407)	(0.000)	(7.266)	(0.001)	(187.533)	(274.141)	(0.413)
	3	29.960	0.007	67.047	0.037	4394.214	2119.323	2.946
		(1.297)	(0.000)	(10.945)	(0.002)	(297.932)	(525.330)	(0.428)
	4	36.965	0.007	77.008	0.036	5575.608	2618.059	3.040
		(1.827)	(0.001)	(8.009)	(0.002)	(498.744)	(559.858)	(0.299)
	5	12.902	0.009	59.966	0.057	1411.104	1222.301	2.128
		(0.864)	(0.001)	(16.309)	(0.003)	(117.148)	(436.699)	(0.272)
	6	16.102	0.006	99.206	0.045	2879.162	2629.775	3.260
		(5.465)	(0.002)	(15.348)	(0.008)	(824.214)	(985.798)	(0.291)
	7	19.104	0.005	111.290	0.041	3820.736	3425.548	2.905
		(4.406)	(0.000)	(14.473)	(0.002)	(881.200)	(552.017)	(0.319)
	8	21.454	0.005	113.428	0.039	4290.766	3704.182	3.168
		(8.778)	(0.000)	(22.591)	(0.005)	(1755.629)	(1188.317)	(0.177)
2	1	14.943	0.009	56.663	0.044	1782.252	1501.048	2.644
		(1.241)	(0.002)	(3.372)	(0.008)	(463.677)	(309.900)	(0.275)
	2	24.706	0.008	59.837	0.040	3169.560	1879.292	2.578
		(1.639)	(0.000)	(2.224)	(0.004)	(273.390)	(236.136)	(0.148)
	3	33.696	0.008	61.102	0.036	4142.645	2323.008	2.337
		(1.507)	(0.000)	(8.364)	(0.003)	(290.727)	(648.882)	(0.111)
	4	48.741	0.008	75.022	0.035	6106.236	3255.198	2.705
		(3.684)	(0.000)	(3.959)	(0.002)	(542.996)	(372.522)	(0.161)
	5	16.573	0.003	90.516	0.042	6291.708	2516.545	2.137
		(1.214)	(0.000)	(7.977)	(0.003)	(839.807)	(432.805)	(0.127)
	6	24.916	0.003	99.914	0.037	10138.654	3237.435	2.298
		(1.964)	(0.001)	(21.712)	(0.004)	(2984.841)	(1148.321)	(0.236)
	7	35.578	0.004	111.109	0.036	10077.746	3634.214	2.487
		(5.222)	(0.002)	(11.950)	(0.002)	(3898.535)	(467.727)	(0.112)
	8	27.740	0.015	83.029	0.046	4018.672	2978.959	1.586
		(5.685)	(0.007)	(27.587)	(0.011)	(5721.221)	(1478.243)	(0.255)

Table 15. (Continued).

Subj	Cond	F1	T1	F2	T2	LrateF1	LrateF2	Imp100ms
3	1	16.972	0.009	62.357	0.042	2176.693	2023.216	2.831
		(1.475)	(0.003)	(3.024)	(0.013)	(756.347)	(910.954)	(0.235)
	2	21.637	0.008	67.879	0.040	2961.421	2355.103	2.646
		(1.989)	(0.001)	(7.207)	(0.002)	(273.365)	(363.798)	(0.249)
	3	29.154	0.009	72.095	0.043	3165.687	2323.416	3.071
		(2.191)	(0.002)	(10.587)	(0.005)	(420.962)	(599.447)	(0.204)
	4	33.588	0.009	70.654	0.041	3732.684	2231.432	3.094
		(1.200)	(0.001)	(4.346)	(0.003)	(244.717)	(303.201)	(0.195)
	5	11.826	0.007	83.788	0.047	1823.192	2170.859	2.555
		(0.326)	(0.002)	(16.826)	(0.006)	(496.826)	(680.876)	(0.289)
	6	16.612	0.008	57.034	0.051	1918.062	1288.435	2.592
		(1.024)	(0.001)	(4.352)	(0.002)	(101.953)	(128.088)	(0.133)
	7	21.876	0.009	76.457	0.047	2497.105	2037.871	2.941
		(1.908)	(0.001)	(12.497)	(0.004)	(304.448)	(552.711)	(0.135)
	8	28.438	0.009	102.998	0.043	3371.620	3122.584	3.152
		(2.582)	(0.001)	(16.235)	(0.003)	(360.208)	(705.069)	(0.080)
4	1	13.37	0.004	46.163	0.033	3043.1	1843.852	2.125
		(0.812)	(0.001)	(4.218)	(0.002)	(561.968)	(256.979)	(0.124)
	2	18.945	0.004	60.008	0.029	4413.816	2954.634	2.374
		(0.937)	(0.001)	(3.119)	(0.003)	(1026.233)	(378.426)	(0.190)
	3	26.204	0.006	74.364	0.032	4639.299	3314.515	2.755
		(1.295)	(0.000)	(7.246)	(0.001)	(358.633)	(491.334)	(0.218)
	4	29.719	0.006	90.660	0.030	4959.301	4388.854	2.966
		(3.165)	(0.000)	(9.644)	(0.003)	(525.967)	(874.266)	(0.212)
	5	11.040	0.005	68.385	0.040	2395.213	2078.785	2.234
		(1.175)	(0.001)	(10.688)	(0.004)	(624.399)	(484.826)	(0.158)
	6	15.040	0.004	75.603	0.035	4278.042	2571.014	2.358
		(0.695)	(0.001)	(16.962)	(0.003)	(1101.549)	(909.669)	(0.131)
	7	22.110	0.006	89.865	0.037	4137.515	2919.104	2.580
		(2.365)	(0.002)	(11.501)	(0.003)	(1819.490)	(507.702)	(0.146)
	8	31.039	0.008	103.400	0.040	4241.440	3287.660	2.888
		(0.793)	(0.000)	(12.298)	(0.002)	(241.054)	(589.216)	(0.073)

Table 15. (Continued).

Subj	Cond	F1	T1	F2	T2	LrateF1	LrateF2	Imp100ms
5	1	14.562	0.005	65.036	0.034	3945.385	2648.734	2.897
		(1.239)	(0.002)	(4.817)	(0.006)	(3060.731)	(582.603)	(0.177)
	2	22.962	0.005	76.882	0.035	4860.787	3350.633	2.849
		(3.005)	(0.002)	(10.574)	(0.006)	(1752.020)	(861.154)	(0.303)
	3	30.806	0.009	66.878	0.045	3301.938	1858.342	3.049
		(2.006)	(0.000)	(5.234)	(0.003)	(203.254)	(217.557)	(0.088)
	4	41.404	0.008	94.274	0.040	5017.981	3157.898	3.620
		(2.912)	(0.001)	(11.798)	(0.004)	(492.084)	(772.834)	(0.299)
	5	12.800	0.005	78.248	0.047	3247.035	1887.616	2.551
		(1.993)	(0.003)	(26.315)	(0.006)	(2128.701)	(858.754)	(0.108)
	6	17.633	0.005	109.725	0.038	4221.010	3380.844	2.788
		(1.993)	(0.002)	(16.681)	(0.004)	(2170.789)	(871.950)	(0.332)
	7	24.744	0.007	117.570	0.038	3544.255	3835.116	3.058
		(1.234)	(0.001)	(24.434)	(0.000)	(252.293)	(961.056)	(0.185)
	8	30.113	0.007	142.469	0.034	4671.611	5284.112	3.259
		(1.629)	(0.001)	(43.967)	(0.003)	(527.599)	(2371.338)	(0.239)
6	1	11.663	0.005	45.111	0.034	2586.656	1722.246	2.010
		(1.802)	(0.002)	(5.972)	(0.005)	(713.660)	(379.658)	(0.307)
	2	16.030	0.007	47.471	0.035	2477.842	1744.926	2.132
		(1.033)	(0.001)	(3.256)	(0.002)	(498.935)	(162.674)	(0.168)
	3	20.365	0.005	63.254	0.028	3953.572	3004.724	2.453
		(1.122)	(0.000)	(2.590)	(0.002)	(300.540)	(258.031)	(0.082)
	4	24.515	0.006	71.292	0.027	4533.446	3707.704	2.670
		(2.844)	(0.001)	(5.983)	(0.003)	(854.673)	(445.048)	(0.214)
	5	9.751	0.003	66.401	0.037	4479.308	2051.657	1.920
		(1.005)	(0.001)	(21.102)	(0.004)	(1340.487)	(785.300)	(0.267)
	6	17.248	0.003	79.330	0.037	6908.570	2391.694	2.070
		(2.525)	(0.000)	(15.824)	(0.003)	(2362.890)	(640.695)	(0.207)
	7	24.222	0.003	86.874	0.036	11729.940	2655.882	2.159
		(1.262)	(0.001)	(9.992)	(0.003)	(3692.451)	(454.028)	(0.285)
	8	27.184	0.003	91.132	0.034	11550.483	3195.038	2.413
		(2.444)	(0.000)	(24.307)	(0.003)	(3837.962)	(1160.427)	(0.080)

Table 15. (Continued).

Subj	Cond	F1	T1	F2	T2	LrateF1	LrateF2	Imp100ms
7	1	15.307	0.014	41.901	0.068	1109.878	691.569	2.293
		(1.843)	(0.001)	(7.159)	(0.007)	(160.203)	(219.679)	(0.207)
	2	19.020	0.013	37.567	0.076	1408.890	499.472	2.369
		(1.824)	(0.000)	(8.174)	(0.010)	(131.655)	(291.522)	(0.201)
	3	28.075	0.013	43.882	0.062	2055.335	781.966	2.680
		(7.126)	(0.001)	(9.033)	(0.010)	(522.697)	(394.273)	(0.236)
	4	35.312	0.012	47.606	0.053	2895.718	1010.950	2.696
		(1.370)	(0.001)	(6.391)	(0.004)	(382.013)	(312.622)	(0.143)
	5	11.707	0.018	34.278	0.076	671.358	445.292	1.984
		(2.891)	(0.003)	(15.119)	(0.007)	(179.650)	(248.799)	(0.371)
	6	19.368	0.013	49.276	0.065	1525.884	835.132	2.479
		(2.692)	(0.001)	(17.247)	(0.009)	(262.909)	(536.589)	(0.109)
	7	23.666	0.012	41.515	0.063	1994.662	674.427	2.353
		(2.639)	(0.002)	(11.007)	(0.009)	(176.021)	(319.665)	(0.143)
	8	32.609	0.011	46.573	0.054	2978.313	929.230	2.481
		(3.983)	(0.001)	(23.282)	(0.009)	(351.086)	(731.633)	(0.227)
8	1	18.087	0.009	57.483	0.046	1915.375	1598.794	2.419
		(1.904)	(0.001)	(8.113)	(0.006)	(271.563)	(624.209)	(0.149)
	2	26.983	0.009	46.366	0.048	2860.967	971.276	2.498
		(2.516)	(0.001)	(7.572)	(0.002)	(403.270)	(309.023)	(0.124)
	3	38.655	0.010	62.989	0.045	3943.224	1568.769	2.955
		(2.362)	(0.001)	(14.475)	(0.004)	(316.405)	(657.310)	(0.148)
	4	47.447	0.010	64.744	0.043	4884.911	1694.861	3.060
		(1.922)	(0.001)	(10.880)	(0.004)	(636.899)	(539.250)	(0.123)
	5	18.117	0.008	42.601	0.053	2373.732	859.657	2.072
		(1.680)	(0.002)	(11.736)	(0.010)	(366.812)	(359.883)	(0.080)
	6	24.643	0.007	60.529	0.048	3587.370	1520.868	2.375
		(2.090)	(0.001)	(17.661)	(0.007)	(867.007)	(726.567)	(0.142)
	7	32.564	0.007	48.962	0.045	4932.338	1130.369	2.757
		(4.090)	(0.002)	(9.898)	(0.003)	(2051.122)	(217.343)	(0.147)
	8	41.145	0.007	68.975	0.047	5943.835	1806.626	2.886
		(5.655)	(0.001)	(24.834)	(0.006)	(1075.417)	(951.399)	(0.103)

Table 15. (Continued).

Subj	Cond	F1	T1	F2	T2	LrateF1	LrateF2	Imp100ms
9	1	0.000	0.000	71.288	0.018	0.000	4042.692	2.948
		(0.000)	(0.000)	(4.629)	(0.005)	(0.000)	(962.541)	(0.182)
	2	19.164	0.008	78.063	0.039	2417.948	2777.770	3.367
		(1.171)	(0.001)	(6.107)	(0.002)	(209.164)	(395.065)	(0.230)
	3	27.707	0.008	81.600	0.038	3746.693	2918.404	3.623
		(1.616)	(0.001)	(10.735)	(0.000)	(600.696)	(468.009)	(0.369)
	4	34.895	0.008	108.610	0.036	4673.834	4266.028	4.145
		(0.533)	(0.000)	(7.496)	(0.002)	(346.059)	(622.202)	(0.165)
	5	7.704	0.006	79.341	0.039	1418.502	2890.295	2.097
		(0.532)	(0.001)	(18.392)	(0.005)	(194.850)	(909.732)	(0.146)
	6	15.382	0.003	79.367	0.039	5590.590	2566.586	2.692
		(1.800)	(0.000)	(18.312)	(0.005)	(1329.696)	(968.098)	(0.112)
	7	21.913	0.005	67.997	0.043	4795.974	1853.689	3.088
		(2.735)	(0.001)	(12.353)	(0.003)	(947.578)	(458.033)	(0.252)
	8	27.745	0.003	93.808	0.037	7731.527	2989.882	3.391
		(4.059)	(0.001)	(26.252)	(0.001)	(1842.901)	(1028.213)	(0.198)
10	1	15.232	0.011	43.188	0.052	1402.322	902.399	2.391
		(0.892)	(0.002)	(4.545)	(0.004)	(262.201)	(228.746)	(0.180)
	2	25.144	0.013	55.261	0.053	1988.238	1167.860	3.087
		(1.143)	(0.000)	(14.374)	(0.004)	(108.515)	(508.307)	(0.411)
	3	30.957	0.012	60.824	0.047	2583.175	1469.694	3.237
		(2.398)	(0.001)	(7.330)	(0.002)	(184.627)	(331.738)	(0.363)
	4	36.044	0.012	59.150	0.047	3081.058	1379.921	3.238
		(0.697)	(0.001)	(3.793)	(0.004)	(386.999)	(164.557)	(0.111)
	5	18.620	0.009	48.500	0.059	2126.267	799.596	2.695
		(0.530)	(0.001)	(4.410)	(0.005)	(220.703)	(149.638)	(0.144)
	6	27.200	0.010	51.703	0.058	2659.117	842.706	3.121
		(1.081)	(0.001)	(11.548)	(0.006)	(324.828)	(302.109)	(0.298)
	7	34.146	0.010	58.016	0.058	3421.858	893.098	3.417
		(1.739)	(0.001)	(5.772)	(0.002)	(227.472)	(180.576)	(0.135)
	8	41.501	0.009	66.597	0.053	4590.208	1273.276	3.559
		(2.558)	(0.001)	(17.501)	(0.006)	(733.097)	(573.207)	(0.195)

Note: Force unit is in N/kg and time unit is in s.
Loading rate unit is in N/kg/s and Impulse unit is in (N/kg)·s.
Standard deviation values are in parenthesis.
The definitions of variables are in Appendix A.

Table 16. Subject means and standard deviations of VGRF variables (Group 2).

Subj	Cond	F1	T1	F2	T2	LrateF1	LrateF2	Imp100ms
1	1	-	-	64.951	0.017	-	3574.580	2.650
				(7.300)	(0.004)		(900.658)	(0.133)
	2	-	-	79.137	0.025	-	3223.487	2.826
				(6.139)	(0.006)		(783.105)	(0.124)
	3	-	-	99.651	0.026	-	3856.677	2.996
				(11.195)	(0.002)		(649.984)	(0.204)
	4	-	-	114.337	0.024	-	4728.326	3.235
				(12.455)	(0.003)		(879.176)	(0.157)
	5	-	-	82.997	0.034	-	2427.334	2.141
				(13.681)	(0.005)		(664.898)	(0.070)
	6	-	-	91.006	0.038	-	2403.052	2.656
				(14.172)	(0.004)		(550.052)	(0.288)
	7	-	-	124.216	0.035	-	3671.220	2.904
				(31.324)	(0.005)		(1351.040)	(0.166)
	8	-	-	113.656	0.027	-	9054.827	3.094
				(40.701)	(0.014)		(11560.677)	(0.131)
2	1	-	-	85.584	0.018	-	4674.473	3.230
				(6.012)	(0.002)		(295.120)	(0.131)
	2	-	-	98.984	0.017	-	5843.073	3.021
				(8.605)	(0.002)		(1216.387)	(0.193)
	3	-	-	126.379	0.017	-	8109.881	3.648
				(5.915)	(0.006)		(2658.625)	(0.275)
	4	-	-	121.316	0.023	-	5826.274	3.389
				(13.845)	(0.008)		(2304.413)	(0.221)
	5	-	-	111.165	0.011	-	10017.021	3.111
				(4.825)	(0.002)		(1632.941)	(0.284)
	6	-	-	129.995	0.021	-	6169.147	2.945
				(0.000)	(0.002)		(692.029)	(0.319)
	7	-	-	129.995	0.028	-	4840.354	3.015
				(0.000)	(0.006)		(1110.457)	(0.281)
	8	-	-	129.259	0.026	-	5091.495	3.143
				(1.646)	(0.006)		(1093.276)	(0.070)

Table 16. (Continued).

Subj	Cond	F1	T1	F2	T2	LrateF1	LrateF2	Imp100ms
3	1	-	-	61.319	0.019	-	3239.655	2.666
				(13.054)	(0.006)		(1032.743)	(0.464)
	2	-	-	70.519	0.020	-	4088.330	2.291
				(17.190)	(0.008)		(2118.153)	(0.509)
	3	-	-	78.344	0.021	-	4331.668	2.423
				(8.724)	(0.009)		(2192.099)	(0.171)
	4	-	-	86.988	0.029	-	3058.721	2.721
				(11.291)	(0.004)		(668.868)	(0.201)
	5	-	-	101.204	0.024	-	5614.674	2.783
				(12.520)	(0.012)		(3663.238)	(0.557)
	6	-	-	99.186	0.031	-	3202.253	1.954
				(17.269)	(0.003)		(875.424)	(0.169)
	7	-	-	113.739	0.031	-	3679.241	2.284
				(10.251)	(0.003)		(531.847)	(0.084)
	8	-	-	116.255	0.030	-	4278.815	2.431
				(23.642)	(0.008)		(2264.801)	(0.179)

Note: Force unit is in N/kg and time unit is in s.
Loading rate unit is in N/kg/s and Impulse unit is in (N/kg)·s.
Standard deviation values are in parenthesis.
The definitions of variables are in Appendix A.
- indicates no value present.

APPENDIX E

ACCELERATION DATA

Table 17. Subject means and standard deviations of acceleration variables (Group 1).

Subj	Cond	AccHead	TaccHead	AccTibia1	TaccTibia1	AccTibia2	TaccTibia2	AtteIndex
1	1	2.293	0.065	8.479	0.012	11.506	0.054	78.951
		(0.340)	(0.009)	(1.150)	(0.001)	(2.350)	(0.006)	(7.682)
	2	3.152	0.054	11.203	0.011	23.108	0.047	86.278
		(0.624)	(0.002)	(1.161)	(0.002)	(4.751)	(0.002)	(1.497)
	3	3.315	0.048	15.340	0.012	23.814	0.044	86.009
		(0.235)	(0.001)	(1.306)	(0.002)	(2.636)	(0.002)	(1.089)
	4	3.941	0.046	18.467	0.014	37.030	0.042	89.085
		(0.703)	(0.002)	(2.080)	(0.001)	(8.998)	(0.002)	(2.116)
	5	2.758	0.072	6.865	0.015	33.398	0.063	91.385
		(0.667)	(0.002)	(0.505)	(0.001)	(9.628)	(0.003)	(2.195)
	6	3.213	0.059	9.993	0.014	46.715	0.051	92.884
		(0.567)	(0.007)	(2.429)	(0.004)	(14.119)	(0.007)	(1.197)
	7	3.132	0.055	14.734	0.013	82.529	0.047	96.161
		(0.469)	(0.002)	(2.216)	(0.001)	(15.819)	(0.001)	(0.459)
	8	3.193	0.050	15.743	0.012	88.279	0.045	96.297
		(0.698)	(0.006)	(2.187)	(0.001)	(23.696)	(0.005)	(0.828)
2	1	2.365	0.052	5.165	0.015	13.135	0.045	81.894
		(0.386)	(0.008)	(1.266)	(0.008)	(2.328)	(0.008)	(1.710)
	2	3.507	0.049	9.201	0.014	21.408	0.042	83.542
		(0.662)	(0.005)	(2.187)	(0.001)	(1.798)	(0.003)	(3.189)
	3	5.509	0.044	18.482	0.014	28.873	0.040	80.939
		(1.233)	(0.001)	(0.944)	(0.001)	(2.300)	(0.003)	(3.612)
	4	6.783	0.042	23.829	0.014	40.979	0.039	83.764
		(2.408)	(0.003)	(1.267)	(0.000)	(5.102)	(0.001)	(3.818)
	5	4.235	0.054	5.367	0.009	38.962	0.048	89.103
		(0.939)	(0.004)	(0.356)	(0.001)	(5.428)	(0.003)	(2.049)
	6	5.236	0.048	8.494	0.009	46.225	0.043	88.658
		(1.806)	(0.003)	(0.829)	(0.001)	(12.366)	(0.004)	(2.377)
	7	5.388	0.048	11.521	0.014	56.112	0.042	90.378
		(0.990)	(0.003)	(0.422)	(0.004)	(8.362)	(0.003)	(1.378)
	8	5.044	0.047	15.254	0.024	48.142	0.051	89.673
		(2.251)	(0.005)	(2.037)	(0.005)	(14.291)	(0.011)	(2.162)

Table 17. (Continued).

Subj	Cond	AccHead	TaccHead	AccTibia1	TaccTibia1	AccTibia2	TaccTibia2	AtteIndex
3	1	3.992	0.051	20.544	0.014	14.238	0.049	60.701
		(0.912)	(0.012)	(11.362)	(0.003)	(5.560)	(0.004)	(39.465)
	2	5.296	0.052	23.183	0.013	39.829	0.046	86.441
		(0.641)	(0.001)	(1.908)	(0.000)	(7.094)	(0.002)	(2.289)
	3	4.770	0.044	33.776	0.015	34.079	0.047	85.703
		(0.925)	(0.010)	(7.754)	(0.002)	(8.903)	(0.004)	(1.795)
	4	4.303	0.044	40.048	0.015	44.840	0.046	90.299
		(0.531)	(0.009)	(3.245)	(0.001)	(7.321)	(0.002)	(1.051)
	5	3.577	0.059	11.178	0.011	42.856	0.053	91.106
		(0.764)	(0.005)	(0.765)	(0.002)	(14.731)	(0.006)	(2.155)
	6	2.081	0.051	13.700	0.013	26.008	0.057	91.909
		(0.285)	(0.014)	(0.676)	(0.000)	(2.597)	(0.002)	(1.526)
	7	2.748	0.039	17.736	0.013	43.058	0.052	92.973
		(0.259)	(0.004)	(1.409)	(0.001)	(14.974)	(0.004)	(2.445)
	8	3.415	0.051	23.587	0.013	76.349	0.048	95.322
		(0.348)	(0.010)	(1.488)	(0.001)	(20.686)	(0.002)	(0.975)
4	1	2.804	0.047	7.445	0.014	25.100	0.037	88.780
		(0.754)	(0.002)	(1.150)	(0.003)	(3.556)	(0.002)	(3.000)
	2	4.239	0.042	9.160	0.015	33.171	0.033	86.980
		(0.991)	(0.003)	(1.046)	(0.005)	(4.150)	(0.005)	(3.904)
	3	3.896	0.043	12.490	0.013	40.132	0.035	90.187
		(0.454)	(0.002)	(0.971)	(0.000)	(4.368)	(0.002)	(1.665)
	4	4.765	0.041	12.691	0.014	52.138	0.033	90.459
		(0.618)	(0.002)	(4.229)	(0.003)	(13.267)	(0.004)	(2.454)
	5	2.207	0.049	4.620	0.020	38.013	0.047	92.307
		(0.709)	(0.003)	(0.276)	(0.004)	(17.428)	(0.003)	(6.514)
	6	2.834	0.043	8.656	0.024	29.539	0.042	87.923
		(0.621)	(0.004)	(1.619)	(0.002)	(15.617)	(0.002)	(8.249)
	7	2.824	0.044	10.876	0.025	58.493	0.043	95.069
		(0.563)	(0.003)	(2.786)	(0.001)	(8.957)	(0.002)	(1.253)
	8	2.470	0.042	12.187	0.024	80.587	0.045	96.878
		(0.413)	(0.005)	(1.733)	(0.002)	(14.543)	(0.002)	(0.601)

Table 17. (Continued).

Subj	Cond	AccHead	TaccHead	AccTibia1	TaccTibia1	AccTibia2	TaccTibia2	AtteIndex
5	1	3.134	0.043	4.883	0.015	23.244	0.036	86.316
		(0.713)	(0.004)	(1.426)	(0.003)	(3.542)	(0.004)	(3.507)
	2	4.287	0.044	11.037	0.017	35.653	0.039	86.571
		(0.765)	(0.007)	(1.934)	(0.003)	(10.941)	(0.005)	(6.537)
	3	3.377	0.048	17.393	0.020	28.591	0.048	88.007
		(0.469)	(0.009)	(1.833)	(0.002)	(5.302)	(0.002)	(1.675)
	4	5.369	0.043	24.454	0.020	52.601	0.042	89.768
		(1.040)	(0.003)	(1.650)	(0.001)	(10.317)	(0.004)	(0.718)
	5	2.497	0.054	5.690	0.018	34.846	0.053	91.516
		(0.604)	(0.008)	(0.575)	(0.004)	(18.546)	(0.006)	(3.544)
	6	3.417	0.046	8.111	0.019	63.900	0.044	94.009
		(0.600)	(0.004)	(1.453)	(0.002)	(21.107)	(0.004)	(2.962)
	7	4.085	0.046	12.550	0.019	77.520	0.044	94.285
		(0.685)	(0.001)	(1.530)	(0.001)	(35.026)	(0.001)	(1.323)
	8	4.540	0.041	15.072	0.018	104.456	0.040	95.555
		(1.391)	(0.002)	(1.256)	(0.000)	(33.325)	(0.003)	(0.777)
6	1	1.706	0.048	9.377	0.013	20.575	0.040	91.592
		(0.165)	(0.008)	(1.128)	(0.000)	(3.296)	(0.006)	(1.185)
	2	2.262	0.045	12.303	0.015	22.493	0.040	89.754
		(0.346)	(0.003)	(0.553)	(0.001)	(2.693)	(0.003)	(2.431)
	3	2.950	0.040	17.145	0.013	35.305	0.033	91.480
		(0.449)	(0.001)	(0.451)	(0.001)	(6.931)	(0.001)	(1.591)
	4	4.679	0.039	25.620	0.015	34.296	0.033	17.386
		(0.287)	(0.003)	(4.418)	(0.005)	(20.427)	(0.005)	(159.292)
	5	1.595	0.049	7.360	0.018	33.792	0.044	95.001
		(0.558)	(0.004)	(0.797)	(0.001)	(15.344)	(0.004)	(1.056)
	6	1.747	0.045	9.983	0.018	49.126	0.044	96.227
		(0.195)	(0.004)	(0.553)	(0.000)	(13.935)	(0.003)	(1.076)
	7	2.121	0.044	11.597	0.015	67.285	0.043	96.819
		(0.517)	(0.005)	(0.916)	(0.003)	(17.617)	(0.003)	(0.451)
	8	2.505	0.038	13.816	0.016	70.211	0.040	96.222
		(0.323)	(0.001)	(0.748)	(0.003)	(21.331)	(0.003)	(0.981)

Table 17. (Continued).

Subj	Cond	AccHead	TaccHead	AccTibia1	TaccTibia1	AccTibia2	TaccTibia2	AtteIndex
7	1	1.579	0.069	6.623	0.028	10.053	0.063	82.284
		(0.422)	(0.010)	(0.844)	(0.001)	(3.577)	(0.010)	(8.819)
	2	2.064	0.092	8.338	0.027	8.842	0.066	70.681
		(0.472)	(0.005)	(1.887)	(0.004)	(6.557)	(0.016)	(12.529)
	3	1.983	0.076	14.290	0.028	17.014	0.057	83.444
		(0.510)	(0.010)	(4.241)	(0.001)	(13.848)	(0.007)	(9.448)
	4	2.428	0.055	19.536	0.025	28.212	0.055	89.616
		(0.237)	(0.004)	(1.204)	(0.004)	(14.996)	(0.002)	(4.716)
	5	1.275	0.089	5.614	0.031	6.220	0.066	72.608
		(0.637)	(0.035)	(0.983)	(0.003)	(6.264)	(0.008)	(15.007)
	6	1.518	0.069	8.742	0.026	16.712	0.065	81.059
		(0.202)	(0.016)	(0.829)	(0.004)	(15.874)	(0.004)	(13.480)
	7	1.599	0.071	11.365	0.023	14.290	0.061	82.841
		(0.184)	(0.016)	(1.986)	(0.005)	(11.853)	(0.004)	(10.228)
	8	2.003	0.052	19.032	0.018	20.848	0.052	86.304
		(0.647)	(0.006)	(2.726)	(0.001)	(16.682)	(0.002)	(7.176)
8	1	2.675	0.057	6.860	0.008	18.563	0.049	85.882
		(0.908)	(0.010)	(0.798)	(0.003)	(3.574)	(0.005)	(2.263)
	2	1.927	0.047	8.777	0.016	17.655	0.051	88.969
		(0.774)	(0.009)	(1.354)	(0.006)	(5.889)	(0.002)	(2.528)
	3	3.100	0.049	16.343	0.016	28.853	0.047	88.800
		(1.203)	(0.014)	(1.798)	(0.001)	(14.000)	(0.002)	(1.698)
	4	3.635	0.041	22.497	0.016	33.897	0.045	88.543
		(0.287)	(0.003)	(4.418)	(0.005)	(20.427)	(0.005)	(159.292)
	5	1.351	0.049	10.794	0.014	18.361	0.060	89.237
		(0.219)	(0.004)	(1.488)	(0.001)	(10.709)	(0.010)	(8.786)
	6	1.674	0.049	14.427	0.012	37.428	0.053	93.685
		(0.469)	(0.009)	(1.070)	(0.001)	(21.557)	(0.007)	(4.856)
	7	2.109	0.040	18.260	0.014	19.572	0.049	86.422
		(0.382)	(0.003)	(3.357)	(0.004)	(9.906)	(0.005)	(7.590)
	8	2.877	0.037	24.212	0.013	41.564	0.049	88.395
		(0.419)	(0.003)	(4.260)	(0.001)	(32.918)	(0.004)	(9.003)

Table 17. (Continued).

Subj	Cond	AccHead	TaccHead	AccTibia1	TaccTibia1	AccTibia2	TaccTibia2	AtteIndex
9	1	3.282	0.034	0.000	0.000	35.744	0.022	90.463
		(1.117)	(0.004)	(0.000)	(0.000)	(6.600)	(0.002)	(3.642)
	2	3.009	0.052	12.439	0.009	19.501	0.044	84.268
		(0.876)	(0.002)	(0.618)	(0.001)	(2.920)	(0.004)	(5.294)
	3	3.636	0.051	13.549	0.008	23.537	0.043	84.638
		(0.854)	(0.002)	(1.093)	(0.001)	(1.747)	(0.002)	(3.044)
	4	5.092	0.049	14.558	0.011	34.028	0.041	85.189
		(1.339)	(0.002)	(0.748)	(0.004)	(3.138)	(0.002)	(2.821)
	5	1.250	0.050	7.193	0.015	41.695	0.045	96.829
		(0.409)	(0.004)	(0.765)	(0.001)	(9.184)	(0.004)	(1.310)
	6	1.978	0.048	9.614	0.012	45.429	0.045	95.104
		(0.369)	(0.004)	(2.128)	(0.002)	(14.718)	(0.004)	(2.231)
	7	2.322	0.049	13.650	0.012	37.963	0.049	93.636
		(0.468)	(0.002)	(0.916)	(0.002)	(11.147)	(0.003)	(1.501)
	8	3.262	0.047	17.181	0.009	80.940	0.044	95.257
		(0.658)	(0.003)	(2.355)	(0.001)	(41.180)	(0.001)	(2.152)
10	1	1.879	0.059	8.838	0.017	10.351	0.053	80.673
		(0.271)	(0.008)	(1.381)	(0.001)	(3.027)	(0.003)	(6.142)
	2	3.264	0.056	15.092	0.017	16.505	0.054	78.966
		(0.503)	(0.004)	(1.315)	(0.001)	(6.315)	(0.001)	(4.516)
	3	3.779	0.054	20.843	0.017	24.878	0.051	83.324
		(1.092)	(0.003)	(1.934)	(0.001)	(12.003)	(0.002)	(4.633)
	4	3.638	0.053	26.694	0.017	24.374	0.053	85.117
		(0.612)	(0.001)	(3.142)	(0.001)	(2.906)	(0.002)	(1.161)
	5	2.303	0.066	10.048	0.015	12.873	0.065	81.337
		(0.261)	(0.004)	(0.844)	(0.001)	(3.476)	(0.004)	(3.960)
	6	3.173	0.066	16.706	0.017	15.799	0.054	71.088
		(0.690)	(0.006)	(1.695)	(0.002)	(12.265)	(0.006)	(15.391)
	7	3.284	0.067	24.273	0.017	18.119	0.061	79.366
		(0.465)	(0.003)	(1.769)	(0.001)	(6.235)	(0.001)	(9.264)
	8	2.891	0.060	18.451	0.019	28.052	0.055	83.710
		(1.135)	(0.003)	(2.749)	(0.001)	(22.142)	(0.003)	(8.999)

Note: Acceleration unit is in g and time unit is in s.
AtteIndex unit is in %.
Standard deviation values are in parenthesis.
The definitions of variables are in Appendix A.

Table 18. Subject means and standard deviations of acceleration variables (Group 2).

Subj	Cond	AccHead	TaccHead	AccTibia1	TaccTibia1	AccTibia2	TaccTibia2	AtteIndex
1	1	4.548	0.028	-	-	36.924	0.021	87.307
		(0.646)	(0.004)			(6.436)	(0.002)	(3.372)
	2	6.267	0.035	-	-	37.630	0.027	82.980
		(0.849)	(0.005)			(7.708)	(0.005)	(2.919)
	3	7.682	0.034	-	-	39.648	0.029	80.699
		(1.415)	(0.001)			(3.513)	(0.003)	(2.481)
	4	8.855	0.032	-	-	53.267	0.027	83.204
		(0.879)	(0.003)			(5.302)	(0.004)	(2.848)
	5	3.446	0.047	-	-	49.635	0.041	93.183
		(1.199)	(0.005)			(12.014)	(0.005)	(0.776)
	6	2.799	0.047	-	-	45.297	0.043	93.662
		(0.553)	(0.006)			(9.117)	(0.005)	(1.399)
	7	4.624	0.039	-	-	86.139	0.040	94.534
		(1.905)	(0.011)			(32.476)	(0.005)	(1.002)
	8	4.831	0.033	-	-	66.786	0.041	90.840
		(2.215)	(0.009)			(38.885)	(0.007)	(5.441)
2	1	7.391	0.028	-	-	28.147	0.022	73.426
		(0.888)	(0.000)			(2.749)	(0.003)	(4.821)
	2	9.292	0.025	-	-	38.034	0.019	74.157
		(0.647)	(0.003)			(9.104)	(0.003)	(8.025)
	3	9.959	0.025	-	-	45.600	0.017	78.322
		(3.205)	(0.003)			(11.494)	(0.003)	(2.636)
	4	9.070	0.032	-	-	39.244	0.019	76.869
		(2.241)	(0.007)			(8.144)	(0.006)	(2.742)
	5	8.756	0.024	-	-	41.464	0.017	77.574
		(2.071)	(0.002)			(7.638)	(0.003)	(9.241)
	6	9.504	0.033	-	-	72.738	0.027	86.712
		(1.487)	(0.002)			(9.972)	(0.002)	(3.064)
	7	9.110	0.039	-	-	70.821	0.034	87.148
		(2.460)	(0.006)			(15.463)	(0.006)	(2.258)
	8	9.545	0.037	-	-	95.235	0.032	89.990
		(3.271)	(0.005)			(24.604)	(0.005)	(2.878)

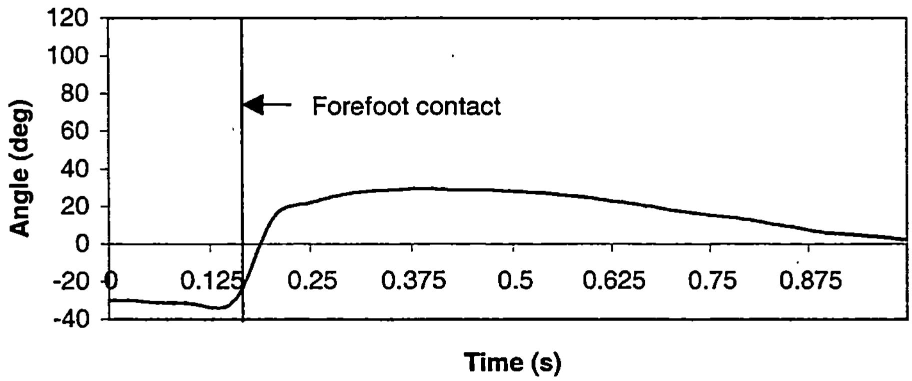
Table 18. (Continued).

Subj	Cond	AccHead	TaccHead	AccTibia1	TaccTibia1	AccTibia2	TaccTibia2	AtteIndex
3	1	2.453	0.029	-	-	24.460	0.021	89.171
		(1.278)	(0.007)			(5.673)	(0.005)	(6.326)
	2	5.020	0.030	-	-	46.553	0.023	88.726
		(1.099)	(0.005)			(11.019)	(0.007)	(3.663)
	3	6.072	0.031	-	-	66.730	0.024	90.824
		(1.006)	(0.009)			(8.998)	(0.009)	(1.617)
	4	6.193	0.038	-	-	69.051	0.031	90.669
		(1.569)	(0.004)			(19.761)	(0.003)	(2.714)
	5	2.655	0.036	-	-	44.031	0.030	93.425
		(0.549)	(0.014)			(12.343)	(0.012)	(2.542)
	6	3.342	0.044	-	-	91.346	0.036	96.213
		(0.988)	(0.002)			(27.184)	(0.003)	(1.000)
	7	4.262	0.039	-	-	111.422	0.036	96.095
		(0.974)	(0.004)			(22.145)	(0.003)	(0.932)
	8	4.373	0.038	-	-	130.590	0.036	96.572
		(1.721)	(0.007)			(44.476)	(0.009)	(1.246)

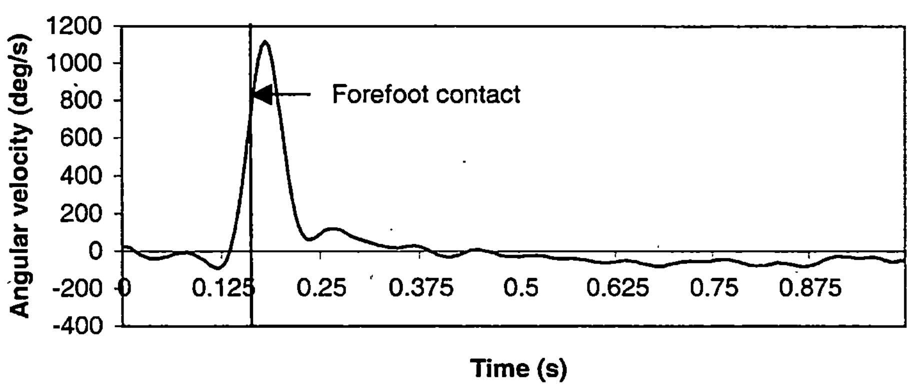
Note: Acceleration unit is in g and time unit is in s.
AtteIndex unit is in %.
Standard deviation values are in parenthesis.
The definitions of variables are in Appendix A.
- indicates no value present.

APPENDIX F

REPRESENTATIVE CURVES

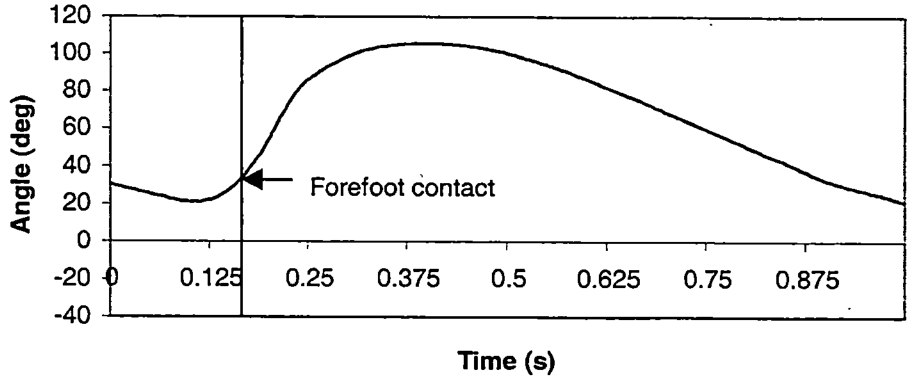


(a) Joint angle

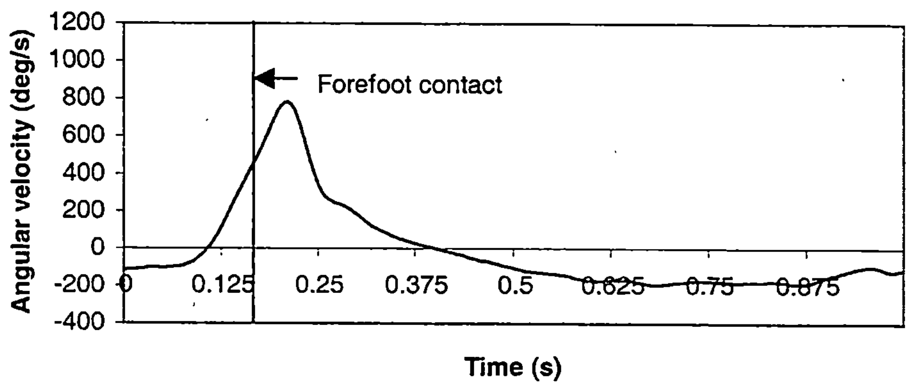


(b) Joint angular velocity

Figure 14. Representative ankle joint curves for barefoot at 60 cm (Group 1).

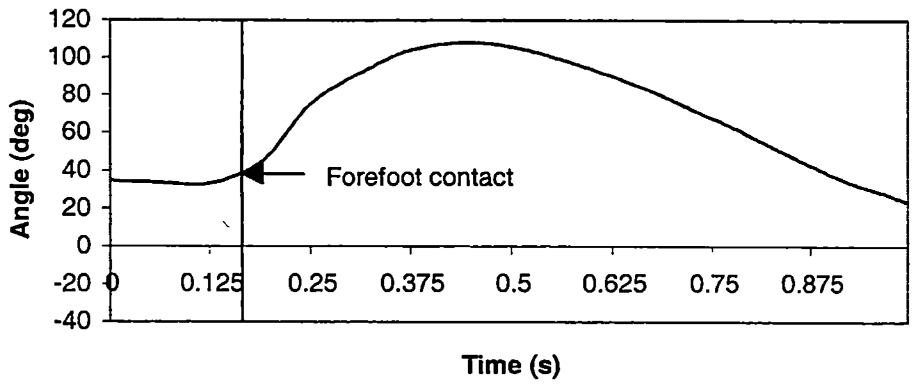


(a) Joint angle

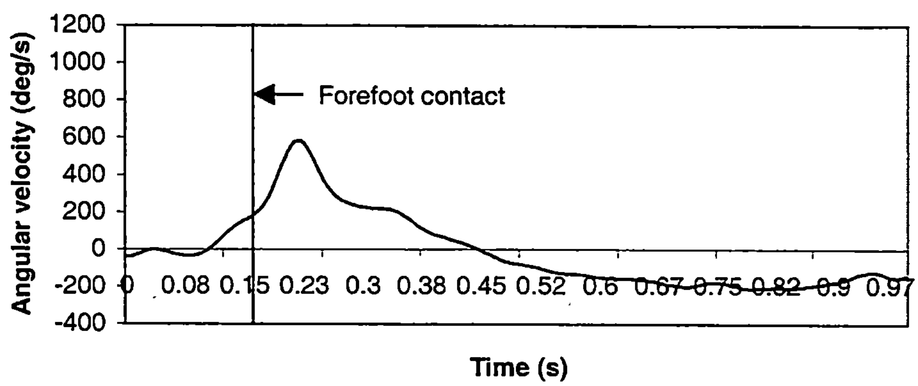


(b) Joint angular velocity

Figure 15. Representative knee joint curves for barefoot at 60 cm (Group 1).

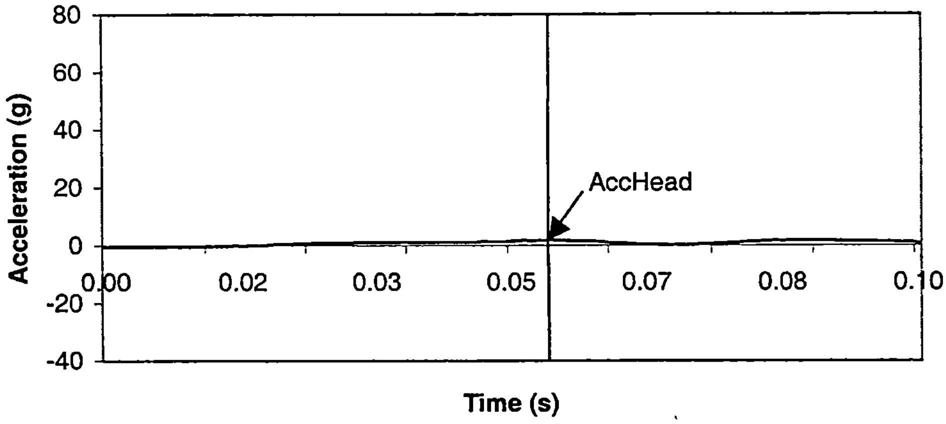


(a) Joint angle

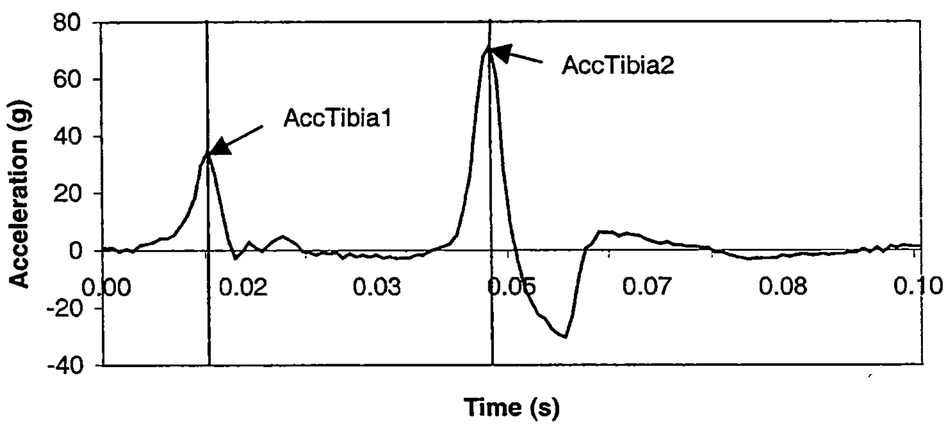


(b) Joint angular velocity

Figure 16. Representative hip joint curves for barefoot at 60 cm (Group 1).



(a) Head acceleration



(b) Tibia acceleration

Figure 17. Representative acceleration curves for barefoot at 60 cm (Group 1).

APPENDIX G

INFORMED CONSENT FORM

Shock attenuation at the tibia and head during landing activities
INFORMED CONSENT FORM

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You are invited to participate in a research study entitled "Shock attenuation at the tibia and head during landing activities" which examines the impact force and impact shock in different surface conditions during landings from different heights.

You are aware that the test session will take approximately one hour including practice and familiarity with the testing protocol. The test session will begin with a warm-up riding a stationary bike for five minutes. The girth and length of lower extremity segments will be measured and recorded afterwards. Reflective markers will be placed on the right side of the shoulder, hip, knee, ankle, heel, and toe. Two miniature accelerometers will be placed on the lower leg and the forehead using double-sided adhesive tapes and Velcro straps. You will perform 40 step-off landings onto a force platform, 5 trials in each of eight experimental conditions. These conditions will include landings from four predetermined heights (11.8, 17.7, 23.6, and 29.5 inches) with and without shoes. You will wear shoes provided by Biomechanics and Sports Medicine Lab during the shoe conditions. The presentation order of different surfaces (shoes and no shoes) and heights will be randomized. During the testing, data from the force platform, the accelerometers, and a video camera will be simultaneously recorded.

Potential Risks and Benefits

The potential risks include an ankle sprain and a muscular strain of the lower extremity from landing in an unbalanced fashion. These risks will be minimized through proper warm-up and sufficient practice before the test. Painful heel pad could be another risk during the barefoot conditions. A pilot study was conducted to determine the appropriate highest height within the tolerance of subjects. It showed that 29.5-inches was tolerable: no performance changes and complaints were reported by the subjects. All tests will be conducted and the equipment handled by the qualified research personnel in the Biomechanics and Sports Medicine Lab. You will be encouraged to warm up actively prior to the testing session so that you feel physically prepared to perform effectively and thus minimize any chances of injuries. In an event of physical injuries resulting from the test, standard first aid procedures will be administered as necessary. At least one researcher with a basic knowledge of athletic training and/or first aid procedures will be present at each test session. The University of Tennessee does not automatically provide reimbursement for medical care or other compensation. Your benefits from participating in this study include better understanding of ground reaction force and impact shock in landing performance. You are welcome to make an appointment to review the data from your test. In addition, if you wish to have a copy of the results of the study, please let the investigator know.

Confidentiality

Your identity as a subject will be held in a strict confidential manner during and after the study. The description of your data will be coded numerically and will be referred to by a subject number. Only the principal investigator, her advisor and qualified Biomechanics and Sports Medicine Lab personnel will have access to subject information and data. Data will be stored on hard drives of computers in the Biomechanics and Sports Medicine Lab during the study, and will be backed up onto zip disks/CDs and erased from the hard drives after the completion of the study. Subject information sheets, videotapes, and backup data cartridges will be stored in a locked file cabinet in the office of the principal investigator's advisor.

If you have questions at any time about the study or the procedures, or experience adverse effects as a result of participating in this study, you may contact Yeon-Joo Yu at (865) 974-2091 or Songning Zhang at (865) 974-1271. If you have questions about your rights as a participant, contact the Compliance Section of the Office of Research at (865) 974-3466. Your participation is completely voluntary and your decision regarding whether or not to participate will involve no penalty or loss of benefits to which you are otherwise entitled. If you withdraw from the study before data collection is completed, your data will be destroyed.

I have read the above information and agree to participate in this study. I have received a copy of this form.

Participant's name ______________________

Participant's signature ______________________ Date ____________

Investigator ______________________ Date ____________

APPENDIX H

TABLES FOR GROUP 2

Table 19. Means and standard deviations of knee joint kinematic variables (Group 2).

Surface	Height	Cont	Max	Tmax	Min	Tmin	ROM	ContVel	MaxVel	TmaxVel
Shoe	1	27.439	78.675	0.190	19.243	0.320	59.432	324.322	664.765	0.037
		(0.708)	(4.744)	(0.042)	(9.508)	(0.302)	(12.289)	(62.537)	(82.022)	(0.010)
	2	31.132	86.135	0.203	23.140	0.398	62.995	376.322	763.637	0.033
		(1.536)	(6.234)	(0.055)	(10.983)	(0.181)	(10.760)	(22.996)	(116.141)	(0.006)
	3	31.545	89.114	0.199	24.920	0.200	64.194	402.103	793.749	0.034
		(1.420)	(5.248)	(0.045)	(11.747)	(0.346)	(10.389)	(47.160)	(101.497)	(0.002)
	4	31.969	93.972 [c]	0.216	22.498	0.320	71.474	411.417	904.552	0.034
		(0.983)	(7.040)	(0.066)	(8.820)	(0.302)	(5.303)	(153.820)	(216.578)	(0.008)
Barefoot	1	27.869	75.374	0.174	18.850	0.229	56.524	390.649	632.746	0.032
		(5.913)	(7.503)	(0.028)	(9.711)	(0.299)	(13.528)	(111.099)	(82.869)	(0.008)
	2	29.860	84.035	0.210	22.981	0.239	61.054	385.780	686.642	0.034
		(1.763)	(6.440)	(0.060)	(11.799)	(0.317)	(11.038)	(19.237)	(80.711)	(0.003)
	3	31.387	85.276	0.185	23.584	0.238	61.692	376.510	724.963	0.035
		(5.784)	(4.498)	(0.038)	(11.728)	(0.315)	(9.573)	(78.636)	(136.151)	(0.006)
	4	30.522	88.933 [c]	0.182	23.589	0.315	65.344	428.967	775.841	0.036
		(5.255)	(7.733)	(0.040)	(12.140)	(0.295)	(5.234)	(52.106)	(156.099)	(0.005)

Note: Angle and ROM units are in degrees and units of time are in s.
Velocity units are in deg/s.
Standard deviation values are in parenthesis.
[a] denotes significant difference between heights 1 and 2.
[b] denotes significant difference between heights 1 and 3.
[c] denotes significant difference between heights 1 and 4.
[d] denotes significant difference between heights 2 and 3.
[e] denotes significant difference between heights 2 and 4.
[f] denotes significant difference between heights 3 and 4.
* denotes significant difference between the shoe and barefoot conditions on the same landing height.
The definitions of variables are in Appendix A.

Table 20. Means and standard deviations of hip joint kinematic variables (Group 2).

Surface	Height	Cont	Max	Tmax	Min	Tmin	ROM	ContVel	MaxVel	TmaxVel
Shoe	1	29.421	64.607	0.191	20.814	0.320	43.793	197.083	452.207	0.040
		(3.530)	(7.722)	(0.043)	(10.998)	(0.302)	(18.639)	(21.276)	(6.897)	(0.012)
	2	31.141	75.847	0.212	25.238	0.279	50.609	233.947	539.897	0.036
		(1.127)	(10.233)	(0.048)	(10.879)	(0.300)	(13.184)	(30.508)	(55.119)	(0.005)
	3	33.281	89.294	0.238	27.097	0.200	62.198	245.508	603.101 [b]	0.040
		(1.546)	(18.071)	(0.059)	(11.615)	(0.346)	(16.950)	(18.742)	(66.955)	(0.004)
	4	32.569	99.234	0.248	27.205	0.240	72.029	280.767	684.730 [c,e]	0.038
		(1.555)	(25.961)	(0.078)	(10.530)	(0.317)	(23.424)	(48.756)	(103.808)	(0.009)
Barefoot	1	29.701	63.074	0.184	20.557	0.273	42.517	221.016	430.368	0.037
		(4.587)	(5.299)	(0.038)	(11.842)	(0.291)	(17.055)	(57.417)	(15.440)	(0.009)
	2	33.022	88.584	0.243	26.010	0.240	62.574	222.831	514.753	0.040
		(3.000)	(22.867)	(0.070)	(13.471)	(0.317)	(20.052)	(46.131)	(68.195)	(0.004)
	3	34.116	94.939	0.237	26.515	0.200	68.424	212.795	560.161 [b]	0.043
		(1.515)	(20.560)	(0.051)	(13.430)	(0.346)	(16.816)	(98.502)	(59.580)	(0.004)
	4	34.468	105.962	0.246	29.002	0.200	76.960	271.607	651.353 [c,e]	0.045
		(4.612)	(27.515)	(0.074)	(12.995)	(0.346)	(20.270)	(107.168)	(65.461)	(0.003)

Note: Angle and ROM units are in degrees and units of time are in s.
Velocity units are in deg/s.
Standard deviation values are in parenthesis.
[a] denotes significant difference between heights 1 and 2.
[b] denotes significant difference between heights 1 and 3.
[c] denotes significant difference between heights 1 and 4.
[d] denotes significant difference between heights 2 and 3.
[e] denotes significant difference between heights 2 and 4.
[f] denotes significant difference between heights 3 and 4.
* denotes significant difference between the shoe and barefoot conditions on the same landing height.
The definitions of variables are in Appendix A.

Table 21. Means and standard deviations of vertical ground reaction force variables (Group 2).

Surface	Height	F1	T1	F2	T2	LrateF1	LrateF2	Imp100ms
Shoe	1	-	-	70.618	0.018	-	3829.569	2.849
				(13.088)	(0.001)		(750.627)	(0.330)
	2	-	-	82.880	0.021	-	4384.963	2.713
				(14.597)	(0.004)		(1334.748)	(0.378)
	3	-	-	101.458 [b]	0.021	-	5432.742	3.022
				(24.068)	(0.004)		(2330.603)	(0.613)
	4	-	-	107.547 [c]	0.025	-	4537.773	3.115
				(18.143)	(0.003)		(1393.582)	(0.349)
Barefoot	1	-	-	98.456 *	0.023 *	-	6019.677	2.678
				(14.283)	(0.012)		(3811.018)	(0.493)
	2	-	-	106.729	0.030 *	-	3924.817	2.518
				(20.560)	(0.008)		(1984.299)	(0.510)
	3	-	-	122.650	0.031 *	-	4063.605	2.734
				(8.240)	(0.003)		(672.696)	(0.394)
	4	-	-	119.723	0.028	-	6141.712	2.889
				(8.360)	(0.002)		(2555.345)	(0.398)

Note: Force unit is in N/kg and time unit is in s.
Loading rate unit is in N/kg/s.
Impulse unit is in (N/kg)·s.
Standard deviation values are in parenthesis.
[a] denotes significant difference between heights 1 and 2.
[b] denotes significant difference between heights 1 and 3.
[c] denotes significant difference between heights 1 and 4.
[d] denotes significant difference between heights 2 and 3.
[e] denotes significant difference between heights 2 and 4.
[f] denotes significant difference between heights 3 and 4.
* denotes significant difference between the shoe and barefoot conditions on the same landing height.
- denotes no value present.
The definitions of variables are in Appendix A.

Table 22. Means and standard deviations of acceleration variables (Group 2).

Surface	Height	AccHead	TaccHead	AccTibia1	TaccTibia1	AccTibia2	TaccTibia2	AtteIndex
Shoe	1	4.797	0.028	-	-	29.843	0.021	83.301
		(2.479)	(0.001)			(6.403)	(0.001)	(8.603)
	2	6.860	0.030	-	-	40.739	0.023	81.954
		(2.197)	(0.005)			(5.039)	(0.004)	(7.339)
	3	7.904	0.030	-	-	50.659	0.023	83.282
		(1.953)	(0.005)			(14.232)	(0.006)	(6.639)
	4	8.039	0.034	-	-	53.854	0.026	83.581
		(1.602)	(0.003)			(14.912)	(0.006)	(6.908)
Barefoot	1	4.952	0.036	-	-	45.043	0.029	88.061
		(3.318)	(0.011)			(4.179)	(0.012)	(9.082)
	2	5.215	0.041	-	-	69.794	0.036 *	92.196
		(3.724)	(0.007)			(23.165)	(0.008)	(4.917)
	3	5.999	0.039	-	-	89.461 [b],*	0.037 *	92.592
		(2.701)	(0.000)			(20.503)	(0.003)	(4.779)
	4	6.250	0.036	-	-	97.537 [c],*	0.036	92.467
		(2.863)	(0.003)			(31.965)	(0.004)	(3.580)

Note: Acceleration unit is in g and time unit is in s.
Shock attenuation index unit is in %.
Standard deviation values are in parenthesis.
[a] denotes significant difference between heights 1 and 2.
[b] denotes significant difference between heights 1 and 3.
[c] denotes significant difference between heights 1 and 4.
[d] denotes significant difference between heights 2 and 3.
[e] denotes significant difference between heights 2 and 4.
[f] denotes significant difference between heights 3 and 4.
* denotes significant difference between the shoe and barefoot conditions on the same landing height.
- denotes no value present.
The definitions of variables are in Appendix A.

VITA

Yeon-Joo Yu was born in In-Cheon, Korea on November 17, 1973. After she graduated In Myung women's high school in February of 1992, she attended Sang Myung University in Seoul, Korea. She received her Bachelor of Physical Education degree in February of 1996. In March of that same year she began to work in Han-Yang Trading Co., Ltd as a secretary. In January of 1999 she began her graduate studies in Exercise Science with a concentration in Sports Medicine and Biomechanics at the University of Tennessee, Knoxville. As a graduate student, she was involved in several projects including analysis of shock attenuation of the human body during landings and biomechanical analysis of energy attenuation strategy in landings. Upon completion of her thesis, she received the Master of Science degree in human Performance and Sport Studies in May of 2001.