TIBIO-FEMORAL JOINT FORCES DURING THE LANDING PHASE OF DIFFERENT TYPES OF VERTICAL JUMP

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The purpose of this study was to compare the tibio-femoral contact forces during the landing phases of 8 different types of vertical jump (squat, countermovement, hop approach and drop jumps each with and without the use of arms). Data were collected from eight males and eight females. Two S-VHS camcorders and a force platform were used to obtain the 3-D kinematics and kinetics of the knee joint. Activities of selected muscles spanning the knee joint were monitored using surface electromyographic (EMG) techniques. The EMG-assisted optimization model was used to estimate the tibio-femoral joint forces. The peak compressive contact forces ranged from 3-5 body weight (BW) and from 2.5-3.7 BW for the males and females, respectively. These loads seldom fell within the range that is considered to be damaging to the cartilage at the knee.

KEY WORDS: knee joint force, EMG-assisted optimization model.

INTRODUCTION: Jumping and landing are phases in many activities such as volleyball and basketball during which the human body experiences tremendous impact forces and joint moments. Greater impact forces and joint moments during jumping and landing have been intuitively linked to injury potential. Many injuries associated with jumping and landing activities occur in the lower extremities with the knee joint being a primary injury site.

The ability of the musculoskeletal system to attenuate impact forces is critical in the prevention of injury. When attempting to understand the injury mechanism in and around the knee joint, we should first know how forces are transmitted across the knee joint by internal structures. Because the knee joint is a common injury site for jumping and landing related injuries, and the internal forces acting on different structures of the knee joint during these activities are currently not well documented, further in-depth investigations are needed to fill such a void. The purpose of this study was (a) to estimate the tibio-femoral contact forces during the landing phase of eight different types of vertical jump (squat, countermovement, hop approach and drop jumps each with and without the use of their arms) using musculoskeletal modeling techniques and (b) to determine whether there are significant differences in tibio-femoral contact force between genders and among the eight types of jump.

METHODS: Eight males (age = 21.9 1.6 yrs) and eight females (age = 20.6 0.5 yrs) with no known musculoskeletal disorders and exercise regularly were recruited as the subjects.

Radiography: Sagittal view radiographs of the right knee were taken from each participant at seven different knee flexion angles (5°, 20°, 35°, 50°, 70°, 90°, and 110°). The participant sat on a stool located next to an x-ray film and performed isometric knee extensions with maximal effort when the radiographs were taken. The knee flexion angle (ØK) was defined as the angle between the distal extension of the thigh and the shank. Two metal pins with lengths of 185.4 mm and 152.4 mm were placed on the anterior surface of the right lower thigh and upper shank for spatial reference.

EMG Recordings: To assess the myoelectric activities of selected knee muscles, seven pairs of surface electrodes with on-site preamplification circuitry (Liberty Technology MYO115 electrode, gain = 1,000, input impedance > 1014? , CMRR > 90 dB, frequency response = bandpass 3 dB at 90 and 500 Hz, center-to-center distance = 1.5 cm) were attached to the rightside of the lower extremity: vastus lateralis (VL), vastus medialis (VM), vastus intermidius (VI), rectus femoris (RF), biceps femoris short head (BF), medial gastrocnemius (GM) and lateral gastrocnemius (GL).

Trials: After a 5-min warm-up on a bicycle ergometer, the subject was asked to perform eight types of vertical jump with maximum effort in random order:

1)squat jump without arm movement (SJ) - a squat position was adopted when the jump was initiated.
2) squat jump with arm movement (SJA) - same as SJ, except that the subject used his/her arms during the jump.
3) countermovement jump without arm movement (CMJ) - a lowering of the body preceding the jump (countermovement) performed from a standing posture.
4) countermovement jump with arm movement (CMJA).
5) hop jump without arm movement (HJ) - a one step approach followed by a CMJ.
6) hop jump with arm movement (HJA).
7) drop jump without arm movement (DJ) - a jump performed immediately after the landing of a drop-off from a height of 0.4 m.
8) drop jump with arm movement (DJA).

For jumps without arm movement, the subject's hands were held to his/her sides throughout the jump. The ground reaction forces acting on the right foot during the takeoff (if applicable) and landing were recorded by an AMTI force platform (model OR6-3). Motions were recorded using two S-VHS camcorders (Panasonic AG455, 60 fields/s). For spatial reference, a Peak calibration frame (2 m X 2 m X 2.3 m object space, 25 control points) was videotaped at the beginning of each data collection session. For each jump type, the subject was asked to repeat trials until three usable trials were obtained. The rest intervals between consecutive trials were approximately 5 min. The subject was asked to rate his/her own performance using a 5-point scale (5 = excellent, 0 = poor) at the end of each trial.

Data Reduction: For each subject, the trial with the highest rating for each jump type was selected for analysis. Therefore, a total of 128 trials (16 subjects x 8 types) was analyzed. For the purpose of this study, the landing phase was defined as the duration from landing to lowest mid-hip position.

The raw EMG signals were filtered using a recursive digital filter (Mathlab Elliptic filter, 10-500 Hz band pass) and full-wave rectified. To obtain a smooth EMG profile, the rectified EMG data were further low-pass filtered (single pass, second order Butterworth) at a cutoff frequency of 3 Hz. The largest EMG level for each muscle obtained during an experimental trial was considered the maximum EMG level (EMGmax) for nomalization.

Radiographic images were analyzed using the procedures described in Chow et al. (1999). On each radiographic image, coordinates of selected landmarks were used to determine the effective moment arm of the quadriceps (de). Using regression analysis, a de-ØK relation was obtained for each subject.

Two-dimensional coordinates of body landmarks (right toe, heel, ankle, knee, hip, and anterior superior iliac spine, midpoint between the left and right pubic tubercles and midpoint between the left and right anterior superior spines) and two markers on short sticks secured on the lateral side of the right thigh and shank were extracted from video images using a Peak 5 motion measurement system for each selected trial. The Direct Linear Transformation (DLT) technique (Abdel-Aziz & Karara, 1971) was used to obtain 3-D coordinates of landmarks and markers. These coordinates were used for defining local reference frames embedded to the pelvis, right thigh, shank, and foot segments. These local coordinate systems were used to define the locations and orientations of muscles as well as joint orientations. The geometric ratio technique proposed by Zatsiorsky and Seluyanov (1983) was used to determine the mass, location of CG, and inertial properties of right shank and foot. Considering a free body diagram of the right shank-plus-foot segment, the resultant knee joint force (FK) and moment (Mk) were computed using the known segmental kinematic and inertial characteristics, and the ground reaction forces and moments.

The knee joint model used in this study included seven muscles (RF, VL, VM, VI, BF, GM and GL). Three-dimensional coordinates of the origins and insertions from Brand et al. (1982) were used in this study. Using a Hill-type muscle model, the initial concentric muscle force was estimated using the normalized muscle force-length (FL) relationship (Nigg & Herzog, 1994), the concentric force-velocity (FV) relationship (Hill, 1938), and the muscular activation (normalized EMG). The initial eccentric muscle force was estimated using the normalized muscle F-L relationship, the eccentric F-V relationship (Hof & Van den Berg, 1981), the muscular activation and the normalized passive force (Woittez et al., 1984). The resultants knee joint force (FK) and moment (MK) represent the net effect of muscle forces, patellar tendon force (FPT), and tibio-femoral contact force (FTF):

$$d_e\, F_Q + r_{BF} \times F_{BF} + r_{GM} \times F_{GM} + r_{GL} \times F_{GL} = M_K \qquad (1)$$

$$F_{PT} + F_{BF} + F_{GM} + F_{GL} + F_{TF} = F_K \qquad (2)$$

where F_Q is the quadriceps force and r is a moment arm vector of a muscle. The FPT was determined using data from x-ray analysis and FQ. The muscle force at a given instant was computed using an EMG-assisted optimization approach (Cholewicki & McGill, 1994). Using normalized EMG data, this approach adjusted the initial muscle forces so that predicted resultant moments (left side of Eq. 1) was the same as the measured MK.
The component of FTF acting on the tibia (computed using Eq. 2) on the sagittal plane of the shank was resolved into compressive (FPTc) and shear (FPTs) components which are parallel and perpendicular to the longitudinal axis of the tibial reference frame, respectively. The peak FPTc and FPTs, expressed as a multiple of the body weight (BW), during the landing phase of each trial were determined.

Data Analysis: For each variable, a two-way analysis of variance (ANOVA) with repeated measures was used to determine whether there were significant differences between sexes and among the eight types of jump. A confidence level of $p < .05$ was used to determine statistical significance.

RESULTS AND DISCUSSION: No significant main effect was found in the jump type. There was also no significant interaction between the two factors. However, the peak mediolateral (M/L) shear contact forces for the males were significantly higher than the corresponding values for the females ($p = .003$). The shear forces were generally in the lateral and posterior directions throughout the landing phase. The peak compressive contact forces ranged from 2,271.2 to 3,672.6 N (3.0 to 5.0 BW) and from 1,415.9 to 2,073.3 N (2.5 to 3.7 BW) for the males and females, respectively. The peak shear forces in the posterior direction ranged from 989.8 to 2,447.7 N (1.3 to 3.2 BW) and from 876.0 to 1,544.5 N (1.6 to 2.8 BW) for the males and females, respectively (Table 1). A posteriorly directed FPTs indicates that the anterior cruciate ligament is loaded.

Table 1 Mean (SD) of Peak Tibio-Femoral Joint Force (xBW).

Jump type	Female			Male			Jump type	Female			Male		
	M/L*	A/P	Vert	M/L*	A/P	Vert		M/L*	A/P	Vert	M/L*	A/P	Vert
SQ	0.4 (0.2)	-2.6 (0.7)	-3.3 ((0.9)	1.1 (0.6)	-2.2 (1.1)	-4.1 (1.0)	**HJ**	0.5 (0.3)	-2.1 (1.1)	-2.5 (1.1)	0.7 (0.2)	-2.1 (1.8)	-4.4 (1.2)
SQA	0.5 (0.5)	-2.8 (1.0)	-3.3 (0.9)	0.5 (0.3)	-2.0 (1.3)	-3.8 (1.6)	**HJA**	0.3 (0.2)	-1.6 (0.8)	-3.5 (1.4)	0.5 (0.4)	-2.1 (1,7)	-3.6 (1.3)
CMJ	0.3 (0.2)	-1.6 (0.6)	-3.1 (1.0)	0.8 (0.6)	-2.0 (0.6)	-4.7 (1.5)	**DJ**	0.4 (0.4)	-1.6 (0.6)	-3.4 (1.3)	0.6 (0.6)	-1.3 (0.5)	-4.1 (1.4)
CMJA	0.3 (0.2)	-1.8 (0.3)	-2.7 (0.8)	0.4 (0.2)	-1.4 (0.9)	-3.0 (1.1)	**DJA**	0.4 (0.3)	-2.6 (0.7)	-3.7 (1.2)	1.4 (2.1)	-3.2 (3.7)	-5.0 (3.4)

Note. M/L: medio(-)/lateral(+). A/P: Antero(+)/posterior(-). Vert: compressive(-). *Significant difference between genders at $p < .01$.

The peak shear forces found in this study are higher than the corresponding forces found during level walking - 0.41 BW, isokinetic knee extensions - 0.6 to 1.3 BW, and descending stairs - 0.64 BW, and similar to values found in squatting - 1.9 to 2.0 BW and fast and slow rise squat exercises - 3.0 BW. The peak compressive forces found in this study are higher than the corresponding forces found during the squat, leg press, and seated knee extension which ranged from 2.9 to 3.6 BW. In general, the compressive forces found in this study are slightly lower than the values found during the fast descent squat - 5.6 BW and isokinetic knee extension - 6.4 BW. During vertical jumps, higher knee contact forces are expected when compared to studies in which moderate activity is used. However, the peak FTF values found in the present study are similar to those reported for different walking activities ranging from 3.0 to 7.1 BW.

The large contact force values in the previous studies may in part be due to the use of simplified muscle models in most early studies (e.g., Smidt, 1973). In these early studies, solutions for muscle forces were based on grouping anatomically and functionally similar muscles. Due to the differences in the method of determining muscle and joint contact forces, and differences in subject sample, cautions must be exercised when comparing values across different studies.

CONCLUSION: Stacoff et al. (1988) found the elastic limit of the cartilage at the knee to be approximately 5,000 N. The present study demonstrated that the tibio-femoral joint was subjected to considerable compressive and A/P shear loads during the landing. However, the loads from the landing seldom fall within the range considered damaging to the cartilage at the knee. Thus, it seems that the magnitude of the load is not the primary factor for causing knee injuries. The cause of injuries to the knee is likely to be related to asymmetrical landings (single leg landing) or prolonged compressive or shear stress acting on the knee joint. An asymmetrical landing causes an abnormal distribution of weight-bearing or increased compression force which exceeds the normal range on one side of the knee joint (Norkin & Levangie, 1983). Prolonged compressive loads may result in instabilities of the knee and a disruption of the normal function.

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