DO GROUND REACTION FORCES REFLECT TIBIOFEMORAL JOINT LOADING IN ANTERIOR CRUCIATE LIGAMENT DEFICIENT SUBJECTS?

Julie R. Steele, University of Wollongong, Australia

KEY WORDS: ACL deficiency, ground reaction forces, tibiofemoral forces.

INTRODUCTION: Physiological loading imposed on the knee during normal activity is composed of two major components: (a) joint forces that the knee must transmit to support, accelerate, or decelerate body mass; and (b) muscle forces acting across the knee to control knee motion and provide stability. The vector sum arising from the joint and muscle forces provides the total load experienced by the knee at any instant in time (Shaw & Murray, 1973).

The tibiofemoral joint force at the knee can be resolved into two main components: (a) the tibiofemoral compression force component, acting perpendicular to the articulating surfaces of the tibia; and (b) the tibiofemoral shear force component, acting in an anterior-posterior direction, in the tangential direction of the joint surface (Nisell, 1985). The tibiofemoral shear force is the force component usually represented as being restrained by the cruciate ligaments (Butler *et al*., 1980). Therefore, the magnitude of the tibiofemoral shear force during motion is an important measure of the potential for anterior cruciate ligament (ACL) injury.

Although the tibiofemoral joint forces are important, Radin *et al*. (1973) claimed that most of the force across the knee came from muscular contraction rather than from joint forces associated with weight bearing. That is, due to a lack of stability afforded by its bony structures, the knee is reliant upon the 12 muscles surrounding the knee joint to provide stabilization, particularly during dynamic activities. The main force created at the knee joint by these muscles is that generated by quadriceps contraction which applies a tractive anterior shear force to the tibial tuberosity. When the knee is flexed between 5 to 10° and 60 to 80°, isolated quadriceps contraction will result in significant anterior tibial translation and ACL strain (Beynnon *et al*., 1995), increasing the probability of ACL injury or a giving-way episode in the ACL deficient (ACLD) knee. However, by attaching posteriorly to the tibia and fibula, hamstring contraction imparts an increasingly posteriorly directed force on the proximal tibia as the knee flexes (Draganich *et al*., 1989). The hamstring muscles thereby function synergistically with the ACL to resist abnormal anterior tibial displacement relative to the femur, induced by quadriceps contraction.

Ground reaction force (GRF) data collected during dynamic tasks are often used to estimate loading imposed on the knee, particularly in studies examining injury mechanisms such as ACL rupture. These data are usually used in preference to calculating the tibiofemoral joint loads as the GRF data are able to be measured relatively easily and quickly, and, thereby, are appropriate for use in clinical settings. However, although GRF data represent the reaction forces applied to an individual's foot to support or decelerate their total body mass, they do not include quantification of muscle forces acting across the knee. As such, GRF data do not include the effects of this main source of knee loading. Should GRF data therefore be used to estimate loading imposed on the knee when examining injury mechanics? As no study was located which addressed this question, the purpose of this study was to examine the relationship between GRF data and tibiofemoral forces generated by control and ACLD patients during a task known to stress the knee, namely abrupt deceleration.

METHODS AND PROCEDURES: Three female and eight male unilateral, functional, chronic, isolated ACLD patients (mean age = 31.6 ± 7.6 years) and 11 control subjects (mean age = 30.4 ± 8.3 years) matched to the patients for age, gender, anthropometry, activity level, and sports experience, and with no history of knee joint disease or trauma participated in the study. Written informed consent was obtained from each subject and all testing was conducted according to the National Health & Medical Research Council Statement on Human Experimentation.

After adequate familiarization, GRF data were sampled (1000 Hz) over 4 s as the subjects landed in single-limb stance on a KISTLER Multichannel force platform after receiving a ball thrown at chest level and decelerating abruptly. This task was selected as it has been identified as a task which causes high tibiofemoral joint shear forces (Steele & Brown, 1997). Data were collected for five successful trials for the subjects' right and left lower limbs. Each subject's deceleration motion in the plane of progression was filmed using a LOCAM (Model 51) 16 mm high speed camera (200 Hz; 1/600 s exposure time), time-synchronized with the force and EMG data using an ultrabright LED system. Two-dimensional kinematic variables were calculated for three representative trials per condition from the smoothed (4th Order Butterworth filter; 11 Hz) digitized data. Kinematic variables selected for analysis included those variables characterizing lower limb alignment and motion from initial contact (IC) of the foot with the force platform through to peak resultant GRF and those variables required for calculating knee joint kinetics. Joint reaction forces and sagittal net moments of force for the knee joint in the sagittal plane were calculated using Newtonian equations of motion and an inverse dynamics approach. The tibiofemoral joint shear and compressive forces were then calculated from the net joint reaction forces and the patellar tendon force occasioned by the net moments and inertial forces predicted to be acting about the knee (Kuster *et al*., 1994). Biomechanical data reported by Nisell (1985) were used to model knee joint musculoskeletal geometry in calculating the tibiofemoral shear forces.

The data were then analyzed using Pearson product moment correlations (r) to determine the relationship between the GRF data and the tibiofemoral force data. The GRF data were characterized by temporal (ms) and magnitude (BW) aspects of the anterior-posterior (F_x) and vertical (F_y) GRF components. The tibiofemoral joint force data were characterized by temporal (ms) and magnitude (BW) aspects the tibiofemoral joint shear (F_S) and compressive (F_C) force components. Where a significant ($p < 0.05$) and strong ($r > 0.9$) correlation between two variables was established, linear regression analysis was used to generate the predictive equation for the dependent variable. For analyses, the lower limbs of the ACLD and control subjects were matched for limb dominance.

RESULTS AND DISCUSSION: Pearson product moment correlation coefficients calculated between the variables for the ACLD and the control subjects are presented in Table 1.

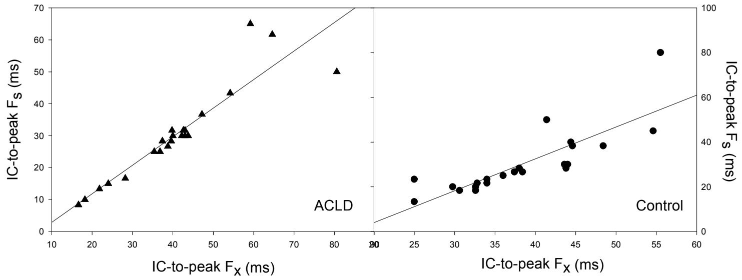
Table 1: Pearson product moment correlation coefficients (r) derived between the GRF and tibiofemoral force data for the ACLD and control subjects.

GRF	Tibiofemoral Force	ACLD (n = 22)	Control (n = 22)	Total (n = 44)
F_x (BW)	F_S (BW)	0.43^{**}	0.90^{**}	0.58^{**}
F_y (BW)	F_C (BW)	0.20	0.74^{**}	0.32^{**}
IC-to-peak F_x (ms)	IC-to-peak F_S (ms)	0.92^{**}	0.82^{**}	0.85^{**}
IC-to-peak F_y (ms)	IC-to-peak F_C (ms)	0.22	0.55^{**}	0.34^{**}

* data for the right and left lower extremities of the 11 subjects were analyzed
** indicates a significant correlation ($p < 0.05$)

The relationship between both the magnitude of F_x and F_s and the magnitude of F_y and F_C was significant and moderate-to-high for the control subjects. However, although the relationship between the magnitude of F_x and F_s was also significant for the ACLD subjects, the correlation was low (Table 1) such that only 18.5% of the variance within F_s could be explained by its relationship with F_x. The relationship between the magnitude of F_y and F_C for the ACLD subjects was even lower (Table 1). Therefore, F_x and F_y were not considered useful for predicting the magnitude of tibiofemoral shear and compressive joint loading in ACLD patients. Similar low correlations were derived between the timing of the peak F_y and the peak F_C relative to IC of the force platform for both subject groups (Table 1). Therefore, timing of peak F_y would not be considered useful for predicting timing of tibiofemoral joint compressive loading in either subject group.

The strongest correlation derived between the GRF data and tibiofemoral force data was for the timing of the peak F_x and peak F_s relative to IC for the ACLD subjects ($r = 0.92$; $p < 0.001$). Although this relationship was also evident for the control subjects, the correlation was lower such that only 67% of the variance within the IC-to-F_s time could be explained by its relationship with the IC-to-F_x time (Table 1). It is therefore suggested that timing of F_x may be used to predict timing of shear forces at the knee during dynamic tasks, particularly in ACLD subjects. The linear regression equations derived to predict the IC-to-peak F_s time from the IC-to-peak F_x time for the ACLD and control subjects are illustrated in Figure 1.



(a) IC-to-peak $F_S = -6.04 + (0.893 \times \text{IC-to-peak } F_X)$ (b) IC-to-peak $F_S = -24.5 + (1.430 \times \text{IC-to-peak } F_X)$

Figure 1: Linear regression equations to predict IC-to-peak F_s time (ms) from IC-to-peak F_x time (ms) for the (a) ACLD subjects and (b) control subjects.

Knowing when the peak F_S occurs relative to IC is of great importance when examining compensatory adaptations used by ACLD patients to protect their knees from giving way episodes. For example, recent research has identified that one of the main compensatory adaptations used by chronic functional ACLD subjects to protect their knee during abrupt deceleration was to alter synchronization of their hamstring muscle onset and peak hamstring muscle activity during the task (Steele & Brown, 1997). That is, subjects with no intact ACL delayed activating their hamstring muscles on their injured lower limb so that peak hamstring activity was more synchronous with the timing of the high F_S which occurred post IC than for the contralateral limb. As these ACLD subjects were landing with their knee near full extension, more synchronous activation of the hamstring muscles with timing of the peak F_S was thought to assist in stabilizing the knee via increasing joint compression and, to a lesser extent, posterior tibial drawer when the knee would be most vulnerable to anterior subluxation.

CONCLUSIONS: It was concluded that the magnitude of GRF data should not be used to predict loading imposed on the tibiofemoral joint in ACLD patients. However, timing of F_x may provide a relatively easy method by which to gain insight into timing of tibiofemoral shear forces at the knee during dynamic tasks and can be predicted using the linear regression equations presented in the present study.

Acknowledgments: The author would like to thank Bridget Munro, Martin Harland, Gavin Pinniger, and Scott Vercoe for assisting with data collection.

REFERENCES:

Beynnon, B. D., Fleming, B. C., Johnson, R. J., Nichols, C. E., Renström, P. A., Pope, M. H. (1995). Anterior Cruciate Ligament Strain Behavior during Rehabilitation Exercises in Vivo. *American Journal of Sports Medicine* **23**, 24-34.

Butler, D. L., Noyes, F. R., Grood, E. S. (1980). Ligamentous Restraints to Anterior-Posterior Drawer in the Human Knee: A Biomechanical Study. *Journal of Bone and Joint Surgery* **62-A**, 259-270.

Draganich, L. F., Jaeger, R. J., Kralj, A. R. (1989). Coactivation of the Hamstrings and Quadriceps during Extens. of the Knee. *J. Bone Joint Surg.* **71-A**, 1075-1081.

Kuster, M., Wood, G. A., Sakurai, S., Blatter, G. (1994). Downhill Walking: A Stressful Task for the Anterior Cruciate Ligament? A Biomechanical Study with Clinical Implications. *Knee Surgery, Sports Traumatology, Arthroscopy* **2**, 2-7.

Nisell, R. (1985). Mechanics of the Knee: A Study of Joint and Muscle Load with Clinical Applications. *Acta Orthopaedica Scandinavica* **56**[Suppl. 216], 1-42

Radin, E. L., Parker, H. G., Pugh, J. W., Steinberg, R. S., Paul, I. L., Rose, R. M. (1973). Response of Joints to Impact Loading III. Relationship between Trabecular Microfractures and Cartilage Degeneration. *Journal of Biomechanics* **6**, 51-57.

Shaw, J. A., Murray, D. G. (1973). Knee Joint Simulator. *Clinical Orthopaedics and Related Research* **94**, 15-23.

Steele, J. R., Brown, J. M. M (1997). Effects of Chronic ACL Deficiency on Muscle Activation Patterns during an Abrupt Deceleration Task. In M. Miyashita et al. (Eds.), *Book of Abstracts of the XVIth Congress of the International Society of Biomechanics* (pp. 56). Tokyo: University of Tokyo.