RELATIONSHIP OF GROUND AND KNEE JOINT REACTION FORCES IN PLYOMETRIC EXERCISES

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The purpose of the current study was to assess the relationship between peak vertical ground reaction force (GRF) and peak knee joint reaction force (KJRF). Eighteen recreationally active college students performed a countermovement jump, single leg jump, and drop jump from a height equal to their vertical jump. Vertical ground reaction forces were assessed with a force plate and KJRF were assessed using a combination of GRF and video data. A Paired samples t-Test revealed GRF to be significantly greater compared to KJRF for all jumps ($p<0.001$). Regression analysis indicated a linear relationship between GRF and KJRF for all the jumps. The R^2 values for each jump were CMJ=0.990; DJ=0.993; SLJ=0.995. These results indicate that GRF data may be a viable alternative for assessing KJRF.

KEYWORDS: jump landing, impact, knee injury

INTRODUCTION: Plyometric exercises are widely used to assess athletic performance, enhance muscular power (Markovic, 2007), bone mass (Bauer et al., 2001), and to reduce the risk of injury (Hewitt et al., 2001). The impact from plyometric landings has been of special interest because of the association with various knee injuries, including tendinosis, anterior cruciate ligament (ACL) injury, and osteoarthritis (Dufek & Bates, 1991).
Additionally, jump landings have been used to evaluate the intensity of various jumps (Jensen & Ebben, 2007), as well as the potential for an osteogenic stimulus (Ebben et al., 2010). The quantification of the impact force during jump landings, specifically on the knee, is critical for injury prevention and proper exercise progression.
Impact forces on the knee or knee joint reaction forces (KJRF) are calculated by acquiring both kinetic and kinematic data obtained by force platforms and video analysis, respectively (Bauer et al., 2001; Simpson & Kanter, 1997). This method of analysis relies on labor intensive and error prone digitization as well as slow video sampling rates which may miss the critical landing impact (Chappell et al., 2002).
The use of ground and knee joint reaction forces to assess various jump landings has been evaluated (Jensen & Ebben, 2007; Simpson & Kanter, 1997); however, the relationship between these aforementioned variables remains equivocal. Therefore, the purpose of this study is to determine if vertical ground reaction forces are related to knee joint reaction forces, which may allow for an indirect quantification of knee joint forces without the use of video analysis.

METHOD: Eighteen recreationally active college students (Mean ± SD Age = 21.9 ± 3.8 years; Height = 174.2 ± 8.2 cm; Weight = 70.46 ± 13.01 kg) volunteered to participate in the study. Participants signed an informed consent form and completed a Physical Activity Readiness-Questionnaire prior to participating in the study. Approval by the Institutional Review Board was obtained prior to commencing the study. Participants performed no strength training in the 48 hours prior to data collection.
Warm-up prior to the study consisted of three minutes of low intensity work on a cycle ergometer, followed by dynamic stretching including one exercise for each major muscle group. Following the warm-up and dynamic stretching exercises, subjects performed two trials of a standing vertical jump, for maximal height to determine the standardized depth jump box height. Participants rested for five minutes prior to beginning testing. The order of the plyometric exercises was randomly assigned, consisting of three trials of each jump; a drop jump (DJ) from a height equal to the subject's vertical jump height, a countermovement

jump with arm swing (CMJ), and a single leg countermovement jump from the left leg (SLJ). For the DJ, subjects were instructed to drop directly down from the box and immediately perform a jump. Participants were instructed to jump for maximal height in all conditions. Participants rested for one minute between trials.

The plyometric exercises were performed by taking off from and landing on a force platform (OR6-5-2000, AMTI, Watertown, MA, USA). Ground Reaction Force (GRF) data were collected at 1000 Hz, real time displayed and saved with the use of computer software (Net Force 2.0, AMTI, Watertown, MA, USA) for later analysis. Video analysis of the exercises were obtained at 60 Hz from the sagittal view using 1 cm reflective markers placed on the greater trochanter, lateral knee joint line, lateral malleolus, and fifth metatarsal. The left leg was chosen for analysis for modeling consistency between various jumps. Markers were digitized and segment accelerations were calculated using Motus 8.5 (Peak Performance Technologies, Englewood, CO). Acceleration of the joint segment center of mass was determined after data was smoothed using a fourth order Butterworth filter (Winter, 1990).

In order to synchronize kinetic and kinematic data, a signal was used to initialize kinetic data collection which also inserted an audio tone in the video data. Data were then combined into a single file and splined to create a file of equal length at 1000 Hz. Because GRF for all jumps but the SLJ would have been distributed between both feet (and therefore both knees), GRF were divided by two prior to calculation of the KJRF. Knee joint reaction forces were calculated using methods previously used (Bauer et al., 2001; Jensen & Ebben, 2007). Peak GRF and KJRF were defined as the maximum values during the landing phase of the various jumps and were presented relative to body weight.

The data were evaluated for the assumptions of normality (skewness and kurtosis) prior to further analysis (Tabachnick & Fidell, 2007). After screening, the data were compared within jumps (CMJ, DJ, and SLJ) for differences between the peak GRF and peak KJRF using a Paired samples t-Test. A regression analysis was performed to assess the relationship of peak GRF to peak KJRF in each of the jumps. All data were evaluated using SPSS 17.0 (SPSS, Chicago, IL). Alpha was specified as $p = 0.05$.

RESULTS:

Paired t-Tests revealed that the peak GRF was significantly greater than peak KJRF for all jumps ($p < 0.001$) (see Table 1). Regression analysis indicated that a linear relationship was present for peak GRF and peak KJRF for all jumps (see Figure 1).

Table 1. Peak GRF and KJRF (mean ± SD) for the CMJ, DJ, and SLJ (n=18).

	CMJ	DJ	SLJ
GRF (BW)	1.989 ± 0.518*	2.017 ± 0.794*	3.002 ± 0.625*
KJRF (BW)	1.949 ± 0.557	1.943 ± 0.799	2.929 ± 0.628
Percent Difference	2.01%	3.67%	2.43%

* Significantly greater than KJRF ($p < 0.001$)

DISCUSSION: Results indicate that peak GRF values were significantly higher than peak KJRF during the CMJ, DJ, and SLJ. However, regression analysis demonstrated a linear relationship between peak GRF and KJRF. These results indicate that GRF data may be a viable alternative for assessing KJRF.

Jensen and Ebben (2007), employing similar methods for assessing joint reaction forces, found SLJ GRF and KJRF to be significantly higher than CMJ GRF and KJRF. Utilizing different methods, Simpson and Kanter (1997) found KJRF values of 2.6 BW while performing traveling jumps, a type of single leg bound found in modern dance. The KJRF values found during the traveling jumps are similar to that of the SLJ in the present study (3.00 BW). The difference in the KJRF values between the two single leg jumps is likely a function of the movement. The acceleration during landing in the SLJ, and the corresponding force, would be directed more vertically as opposed to the horizontal bounds where the resultant force would be more horizontal. These studies however, failed to assess the relationship between GRF and KJRF.

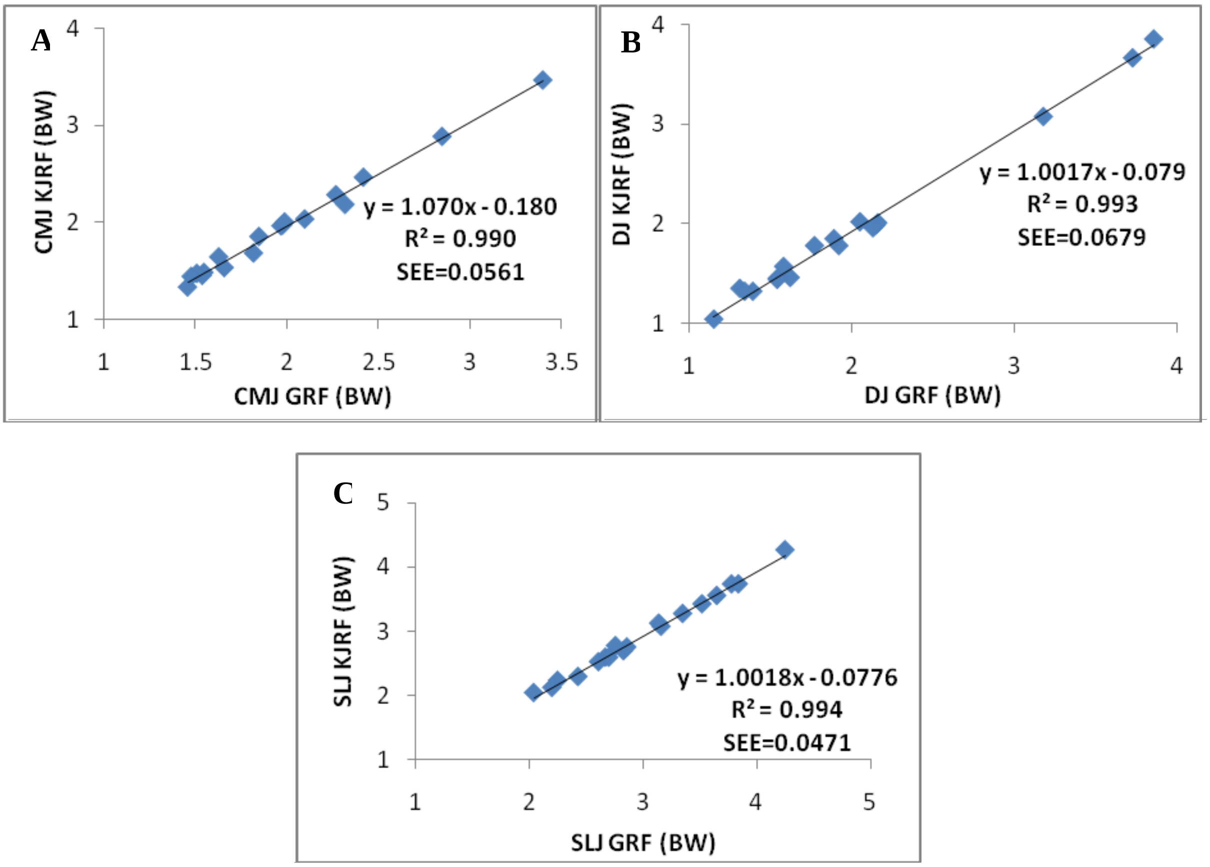

Figure 1. Regression of GRF to KJRF for A (CMJ), B (DJ), C (SLJ) (n = 18).

Previous studies have investigated the correlations between various variables and peak GRF. Results of Peterson and colleagues (2009) demonstrated that peak anterior tibial translation and GRF occurred at the same time when performing drop landings from a height of 40 cm. Anecdotal evidence by Cerulli et al. (2003) indicated that peak ACL strain occurred near the time of peak GRF upon impact during a single left leg jump. Thus, GRF may not only indicate knee joint compressive forces, but also the timing of the tibial translation and ACL strain which are factors that influence ACL injury (Hewitt et al., 2001).
Results of the current study suggest that CMJ, DJ, and SLJ peak KJRF are highly correlated to peak GRF and can be predicted from GRF using linear regression equations. These findings would allow peak KJRF to be calculated without using video analysis, which would be time and labor efficient. However a limitation is that KJRF is not the only variable that should be assessed, as it does not account for shear forces on the knees, which is more important in assessing strain on the ACL (Cerulli et al., 2003). In addition, varus/valgus knee movements are important in assessing the risk of ACL injury (Hewett et al., 2005) and KJRF do not directly account for these variables.

CONCLUSION: Peak GRF values were significantly higher than peak KJRF during the CMJ, DJ, and SLJ, but were highly correlated. These results indicate that GRF data may be a viable alternative for assessing KJRF. The prediction equations for KJRF of the various jumps are as follows: CMJ peak KJRF = 1.07(peak GRF) – 0.18, SLJ peak KJRF = 1.003 (peak GRF) – 0.080, and DJ peak KJRF = 1.002(peak GRF) – 0.079. The ability to assess

KJRF using a force platform will allow practitioners to quantify one of many important variables associated with knee injuries using a relatively inexpensive and time efficient tool.

REFERENCES:

Bauer, J.J., Fuchs, R.K., Smith, G.A., and Snow, C.M. (2001) Quantifying force magnitude and loading rate from drop landings that induce osteogenesis. *Journal of Applied Biomechanics* 17:142-152

Cerulli, G., Benoit D.L., Lamontagne, M., Caraffa, L.,Liti, A. (2003) In vivo anterior cruciate ligament strain behaviour during a rapid deceleration movement. *Knee Surgergy Sports Traumatology and Arthroscopy* 11(5):307-11.

Chappell, J.D., Yu, B., Kirkendall, D.T., and Garrett, W.E. (2002) A comparison of knee kinetics between male and female recreational athletes in stop-jump tasks. *The American Journal of Sports Medicine* 30(2):261-267

Dufek, J.S. and Bates, B.T. (1991) Biomechanical factors associated with injury during landing in jump sports. *Sports Medicine* 12(5):326-337

Ebben, William P; Fauth, McKenzie L; Kaufmann, Clare E; Petushek, Erich J (2010) Magnitude and Rate of Mechanical Loading of a Variety of Exercise Modes. *The Journal of Strength & Conditioning Research*. 24(1):213-217.

Hewett TE, Myers GD, Ford KR, Heidt RS, Colosimo AJ, McLean SG, vanden Bogert AJ, Paterno MV. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes. *American Journal of Sports Medicine*, 33(4), 492-501.

Hewett, T.E., Myer, G.D., and Ford, K.R. (2001) Prevention of Anterior Cruciate Ligament Injuries. *Current Women's Health Reports.* 1:218-224

Jensen, R.L. and Ebben, W.P. (2007) Quantifying plyometric intensity via rate of force development, knee joint and ground reaction forces*. Journal of Strength and Conditioning Research* 21(3): 763-767.

Markovic, G. (2007) Does plyometric training improve vertical jump height? A meta-analytic review. *British Journal of Sports Medicine* 41, 345-355.

Peterson, D., Krong, J., Giphart, E., Steadman, J.R., Torry, M., and Shelburne, K. (2009) Ground reaction force is a predictor of anterior tibial translation during drop landings in healthy adults. *32nd Annual Meeting of the American Society of Biomechanics:* (I. Davis, J. Challis, J. Gottschall, and Steve McCaw, chairs) p. 32

Simpson, K.J. and Kanter, L. (2008) Jump distance of dance landings influencing internal joint forces: I. axial forces. *Medicine & Science in Sports & Exercise* 29(7):916-27.

Tabachnick BG, Fidell LS. (2007) *Using multivariate statistics. 5th ed*. Allyn & Bacon, Inc., Boston, MA.

Winter, D.A. (1990) *Biomechanics and motor control of human movement* (2nd Ed). New York: Wiley Interscience.

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