COMPARISON OF MOMENTS AND SHEAR FORCES OF THE HIP AND KNEE DURING STEP UPS AND SINGLE LEG SQUATS

Adam Bruenger, Jason Carruth, and Steven Tucker

KPED, University of Central Arkansas, Conway, AR, USA

The purpose of this study was to evaluate moments and shear forces at the hip and knee during step ups and single leg squats. Subjects were 12 weight trained adults. Each subject performed 3 repetitions of step ups and single leg squats using 70% of 1 repetition maximum. 2 X 2 (lift X phase (eccentric/concentric)) repeated measures ANOVAs were performed for each dependent variable. Significant interaction effects ($p<0.05$) were observed for knee shear force, hip shear force, and hip moment. Main effects ($p<0.05$) for both lift and phase were observed for knee moment. The single leg squat produced greater hip and knee moments with less absolute weight. The single leg squat may be a better exercise for healthy individuals, but may be problematic for those with a hip or knee dysfunction.

KEY WORDS: lower extremity, strength training, joint stress.

INTRODUCTION: Although the inclusion of functional exercises in training has increased in popularity, there is limited research on functional lower extremity exercises. Functional exercises are ones that attempt to mimic demands of sports movements and, for the lower extremity, typically have unbalanced loading of the legs (Keogh, 1999; Henry, 2011). Fauth et al. (2010) and Wurm, Garceau, VanderZanden, Fauth, & Ebben (2010) evaluated ground reaction forces and rate of force production of females and males, respectively, during functional exercises (the step up and lunge) and traditional exercises (the squat and dead lift). Likewise, single leg squats (Escamilla, Zheng, Imamura, et al., 2009; Escamilla, Zheng, Macleod, et al., 2009) have been evaluated for cruciate ligament stress and patellofemoral force. However, no known studies have reported joint moments or shear forces experienced at both the hip and knee during functional exercises such as the step up and single leg squat. As all exercises have the potential to improve performance or cause injury, it is important to understand the stresses created to make an informed decision if such exercises should be included in a training routine. The purpose of this study was to evaluate moments and shear forces at the hip and knee during step ups and single leg squats.

METHODS: Fourteen men who regularly engaged in lower extremity training volunteered for this study. Two participants did not complete all portions of the study and were removed from analysis. Thus, 12 participants (mean ±SD, age 22.5 ±1.2 y, height 174 ±6 cm, mass 80.2 ±6.0 kg, body fat 9.4 ±2.5 %, step up maximum 90.9 ±12.3 kg, single leg squat maximum 84.8 ±11.3 kg) are reported. The study was approved by the institution's internal review board.
Participants completed two testing sessions. The first session determined 1 repetition maximums (1RM) for the single leg squat and step up for the right leg. Order of exercise was randomized and a 10 minute rest was provided between maximums. Participants warmed up for 5 minutes on a cycle ergometer at a rate and resistance of their choosing. The 1RMs were determined using Wilson, Newton, Murphy, & Humphries`s (1993) protocol. Box height for the step ups was set at a height where the participants had 90° angles at the right knee when the foot was on top of the box and there was a 90° angle at the ankle (Figure 1). Box height varied from 38.7 cm to 41.3 cm. Participants started on the ground and performed the concentric portion first for the step up. The same height box was used for support of the left leg during the single leg squat. Participants were instructed to place their heels on a marker and the box was moved to a position where the participants could descend so the right knee was at a 90° angle and the box would not come in contact with the left shin (Figure 1).

The second session took place a minimum of 48 hours after the first session. After warm up on a cycle ergometer, participants were fitted with reflective markers and then completed three repetitions of both step up and single leg squat at 70% of their 1RM. The order of exercise was the same as the 1RM order for each participant. A metronome was set to regulate a cadence of 1-second for both the eccentric and concentric phases. A minimum of a minute rest was allowed between repetitions.

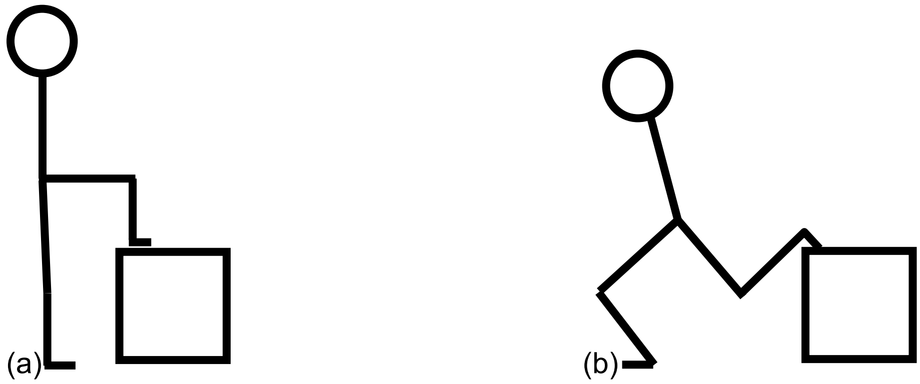

Figure 1: A diagram of the step up (a) and single leg squat (b) box placement

Data were collected via a five camera Vicon 460 motion analysis system (Vicon, Centennial, CO) instrumented with a fixed, in-ground force platform (AMTI BP400600, AMTI, Watertown, MA) and a portable force plateform (Kistler 9286BA, Kistler Instrument Corp., Amherst, NY) placed upon the surface of the step up box. The single leg squats were performed with the right leg positioned on the in-ground force platform and the left leg on the portable force platform (Figure 1). During the step ups, the left leg (support leg) was positioned on the in-ground force platform until the right leg extended.
Video data were recorded at 120 Hz and analog data was collected at 1080 Hz. Data were synchronized and moments and shear forces calculated using Bodybuilder software (Vicon, Centennial, CO) via a modified Golem (Vicon, Centennial, CO) model. Hip centers were determined from greater trochanter markers as opposed to the original model's use of the anterior superior iliac spines due to previous experience with the iliac spine markers being blocked from camera view during significant hip flexion. Moment and shear force data were also smoothed via a 4th order critically damped filter using Matlab software (Mathworks, Natick, MA). The cutoff frequency, determined using the Jackson Knee method, was 9 Hz. Maximal moments and shear forces were determined for both the eccentric and concentric phases.
Moments and shear forces at the hip and knee were evaluated using 2 X 2 (lift X phase) repeated measures ANOVAs for each joint and stress. Statistics were performed using Statistical Packages for Social Sciences (SPSS) v. 17.0 (IBM, Armonk, NY). The *a priori* alpha level was set at $P < 0.05$ and all data are expressed as means ±SD.

RESULTS: Significant interaction effects ($p<0.05$) were observed for knee shear force, hip shear force, and hip moments (Table 1). Main effects ($p<0.05$) for both lift and phase were observed for knee moments. Tukey's HSD post hoc tests were performed to determine specific differences for all significant interaction effects.

Table 1. Maximum Moments and Shear Forces Experienced During Single Leg Squats and Step Ups

	Single Leg Squat (Mean±SD)		Step Up (Mean±SD)	
	Eccentric	Concentric	Eccentric	Concentric
Knee Moments (Nm)*##	188 ±48	185 ±50	142 ±49	133 ±45
Hip Moments (Nm)	243 ±63**	236 ±62**	184 ±17#	217 ±25
Knee Shear Forces (N)	569 ±82	555 ±92	523 ±95	544 ±110
Hip Shear Forces (N)	-990 ±95**#	-977 ±98**#	-674 ±68#	-741 ±67

* = significant (p<0.05) main effect for lift (single leg squat vs step up)
##= signficiant (p<0.05) main effect for phase (eccentric vs concentric)
** = significantly different (p<0.05) than step up eccentric
#= significantly different (p<0.05) than step up concentric

DISCUSSION: This is the first known study to evaluate moments and shear forces at the hip and knee during step ups and single leg squats. One of the most interesting findings of this study was the significantly different hip moments and hip shear forces during the eccentric and concentric portions of the step up. Typically, maximal moments occur at the deepest portion of a squat (Wretenberg, Feng, Lindberg, & Arborelius, 1993) during the switch from the eccentric to the concentric phase. However, the step up in this study was performed where the concentric phase occurred first so there was minimal momentum. The eccentric phase consisted of the participants returning to the ground from the top of the step up box. Different movement strategies were used during the eccentric and concentric portions of the step up. The concentric phase had a movement pattern that reduced knee moments while increasing hip moments. The eccentric phase had the opposite pattern. Part of the change in movement is most likely due to the support leg (left leg in this study) absorbing the force of landing off of the box. The lower moment at the hip would suggest lower hip extensor muscle activation during the eccentric phase of the step up. The step up movement pattern would have to be modified if an athlete started on top of the box so that the eccentric portion occurred first and there was limited contact with the ground by the support leg before starting the concentric phase. Fauth et al. (2010) and Wurm et al. (2010) required participants to perform the step up in this manner but did not measure moments or shear forces. Further research is needed to determine how changing order of eccentric and concentric phases of the step up affects moments and shear forces and also the influence of the support leg on movement patterns used during the step up.

The shear forces and moments in this study were greater than those reported in a previous study of traditional squatting (Gullett, Tillman, Gutierrez, & Chow, 2008). Upon closer inspection, the greater shear forces and moments may be due to stronger individuals in the current study (step up maximum 90.9 ±12.3 kg, single leg squat maximum 84.8 ±11.3 kg) compared to the Gullet et al. (2008) study (88.3 kg back squat, 69.2 kg front squat).

The single leg squat exhibited greater maximal hip shear force, knee moment and hip moment compared to the step up even though the absolute amount of weight lifted was less. Shear forces and moments are used to assess both the potential for adaptation and the potential for injury during an exercise (Gullet et al., 2008; Schoenfeld, 2010). The single leg squat may provide better stimulation for healthy individuals, but may not be appropriate for individuals with previous hip and knee injuries. However, true evaluation cannot occur without inclusion of evaluation of muscle activity of the hip and knee.

CONCLUSION: The single leg squat produced greater hip and knee moments with less absolute weight. The single leg squat may be a better exercise for healthy individuals, but may be problematic for those with hip or knee issues.

REFERENCES:
Baechle, T. R., & Earle, R. W. (2008). *Essentials of strength training and conditioning*.(3rd ed.) Champaign, IL: Human Kinetics.
Escamilla, R. F., Zheng, N., Imamura, R., Macleod, T.D., Edwards, W.B., Hreljac, A., Fleisig, G.S., Wilk, K.E., Moorman, C.T., & Andrews, J.R. (2009). Cruciate ligament force during the wall squat and the one-leg squat. *Medicine and Science in Sport and Exercise*, 41(2), 408-417.
Escamilla, R. F., Zheng, N., Macleod, T.D., Edwards, W.B., Imamura, R., Hreljac, A., Fleisig, G.S., Wilk, K.E., Moorman, C.T., & Andrews, J.R. (2009). Patellofemoral joint force and stress during the wall squat and the one-leg squat. *Medicine and Science in Sport and Exercise*, 41(4), 879-888.
Fauth, M.L., Garceau, L.R., Lutsch, B., Gray, A., Szalkowski, C., Wurm, B. & Ebben, W.P. (2010). Kinetic analysis of lower body resistance training exercises. In: Conference Proceedings of the *XXVII Conference of the International Society of Biomechanics in Sports. Marquette, MI, USA*. July 19-23.
Gullett, JC, Tillman, MD, Gutierrez, GM, & Chow, JW. (2008). A biomechanical comparison of back and front squats in healthy trained individuals. *Journal of Strength and Conditioning Research* 23(1), 284–292.
Henry, T. (2011). Resistance training for Judo: Functional strength training concepts and principles. *Journal of Strength and Conditioning*, 33(6), 40-49.
Keogh, J. (1999). Lower-body resistance training: Increasing functional performance with lunges. *Journal of Strength and Conditioning*, 21(1), 67-72.
Schoenfeld, B.J. (2010) Squatting kinematics and kinetics and their application to exercise performance. *Journal of Strength and Conditioning Research* 24(12), 3497–3506.
Wilson, G.J., Newton, R.U., Murphy, A.J., & Humphries (1993). The optimal training load for the development of dynamic athletic performance. *Medicine and Science in Sports and Exercise*, 25, 1279-1286.
Wretenberg, P., Feng, Y., & Arborelius, U. P. (1996). High- and low-bar squatting techniques during weight-training. *Medicine & Science in Sports & Exercise,* 28(2), 218-224.
Wretenberg, P., Feng, Y., Lindberg, F., & Arborelius, U. P. (1993). Joint moments of force and quadriceps muscle activity during squatting exercise. *Scandinavian Journal of Medicine and Science in Sports,* 3, 244-250.
Wurm, B., Garceau, L.R., VanderZanden, T.L., C. Fauth, M.L.,, & Ebben, W.P. (2010). Ground reaction force and rate of force development during lower body resistance training exercises. In: Conference Proceedings of the *XXVII Conference of the International Society of Biomechanics in Sports. Marquette, MI, USA*. July 19-23.

Acknowledgement: This study was funded by a University of Central Arkansas Research Council grant.