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Center of Pressure Predicts Intra-limb Compensatory Patterns That Shift Demands Away From Knee Extensors During Squatting

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Abstract

The persistence of knee extensor moments deficits following anterior cruciate ligament reconstruction (ACLR) may be attributed to difficulty quantifying inter- and intra-limb compensations clinically. Force plate derived center of pressure (CoP_{pos}) and vertical force (vGRF) may provide valuable information regarding limb and joint loading impairments in this group. This study aimed to determine the: 1) relationship between measures CoP_{pos} and intra-limb extensor moment distribution during a squat, and 2) utility of using CoP_{pos} and vGRF to estimate knee extensor moment deficits post-ACLR. Twenty-four individuals, 142±22.5 days post-ACLR, performed bilateral squats. Ankle (aEXT), knee (kEXT) and hip (hEXT) extensor moments were calculated using three-dimensional kinematics and GRF. Moments, CoP_{pos} and vGRF were identified at peak kEXT. Intra-limb moment distribution was characterized using hEXT/kEXT and aEXT/kEXT ratios. Linear regressions analyzed relationships between CoP_{pos} and hEXT/kEXT and aEXT/kEXT. Stepwise regressions determined if between-limb CoP_{pos} ratio predicted between-limb ratios of hEXT/kEXT and aEXT/kEXT. Stepwise regression determined if between-limb CoP_{pos} and vGRF ratios predicted between-limb kEXT ratio. Results found that CoP_{pos} predicts intra-limb moment distribution (hEXT/kEXT and aEXT/kEXT); more anterior CoP_{pos} related to higher moments at the hip and ankle relative to the knee. In addition, between-limb CoP_{pos} ratio predicts between-limb ratio of hEXT/kEXT and aEXT/kEXT ratios. Together between-limb CoP_{pos} (52%) and vGRF (18%) ratios explained 70% of the variance in between-

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Declaration of Competing Interest

There are no conflict of interest to disclose.

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limb kEXT ratios ($R^2=0.70$, $p < 0.001$). These data suggest that force plate derived CoP_{pos} and vGRF may be important for detection of knee extensor moment deficits in individuals post-ACLR.

Keywords

anterior cruciate ligament reconstruction; compensation; force platforms; center of pressure

1. Introduction

Despite an emphasis on loading the surgical knee in rehabilitation following anterior cruciate ligament reconstruction (ACLR) (Adams et al 2012.; Baumgart et al. 2015) the presence of reduced knee extensor moments are commonly reported across tasks (Baumgart et al 2015.; Labanca et al. 2016; Paterno et al. 2007; Roos et al. 2014; Sigward et al. 2018). Persistence of underloading strategies greater than a year after surgery is concerning as asymmetrical loading during bilateral tasks is thought to contribute to increased risk of a second ACL injury (Paterno et al. 2007). Previous studies demonstrate that individuals utilize strategies that underload the surgical limb and knee extensors during submaximal tasks even in later rehabilitation. Individuals 13 months post-ACLR exhibited a 17% reduction in knee extensor moment in the surgical limb compared to the non-surgical limb during a bilateral squat (Roos et al., 2014). Asymmetry of this magnitude would not be expected at this point of recovery during a squat as individuals are progressed on to more challenging tasks, and are often returned to sports and more demanding activities (Adams et al., 2012; Bizzini et al., 2012; Myer et al., 2006; Waters, 2012).

Difficulty visualizing altered loading patterns may underlie their persistence. A recent study found that individuals 3 months post-ACLR who exhibited a 38% decrease in knee extensor moment in the surgical limb during a bilateral squat had on average a 2 degree differences in knee flexion and no difference in hip flexion angle (Sigward et al., 2018). Underloading of the knee extensors during the squat was accomplished with inter-limb and intra-limb loading compensations that were not reflected in obvious alterations in joint angles. An inter-limb shift in loading (ground reactions forces) to the non-surgical limb explained 62% of the variance in knee extensor deficits in the surgical limb at 3 months post-ACLR. While this compensation could ultimately be detected by measuring under foot forces, it would not capture compensations occurring within the surgical limb. This is important because an intra-limb compensation that shifted the demand away from the knee to the hip explained an additional 23% of the variance in knee extensor deficits at 3 months post-ACLR. Moreover, when these same participants were evaluated 2 months later they continued to exhibit a 30% deficit in knee extensor moment that was only explained by an intra-limb shift to the hip; again in absence of between limb differences in joint angles. The inability to detect altered knee joint loading during this fundamental rehabilitation exercise limits clinician's ability to address it.

As an intra-limb shift in extensor demands is not accomplished through overt alterations in joint kinematics, it is conceivable that manipulation of the position of the center of pressure (CoP_{pos}) may play a role in modulating joint moments. Center of pressure, the point at

which the average location of the ground reaction forces (GRF) act on the foot, can dictate the effect of the vGRF on the joint moments (Gruben and Boehm, 2012). Previous studies support the relationship between medial-lateral and anterior-posterior CoP_{pos} and knee joint moments in the frontal and sagittal planes, respectively (Ferrigno et al. 2016; Kernozek et al., 2018). Theoretically, an increased anterior CoP_{pos} could shift the vGRF vector closer to the knee and further from the hip and ankle joint centers (Figure 1). This is supported by a recent study that reported increased hamstring and gastrocnemius muscle activation with decreased quadriceps activation when healthy participants were asked to shift their center of pressure forward in static squat positions (Kitamura et al., 2019). However, it is not known if individuals following ACLr alter CoP_{pos} in the surgical limb to shift the demands away from the knee extensors toward the hip extensors and ankle plantar flexors. If unilateral adjustments in CoP_{pos} reflect an intra-limb compensation to reduce knee extensor demands in the surgical limb this information could be combined with ground reaction force magnitude to identify knee extensor moment deficits during squatting. Therefore, the purposes of this study were to determine: 1) the relationship between CoP_{pos} and sagittal plane joint moment distribution across the hip, knee and ankle, 2) if between-limb difference in CoP_{pos} were reflective of between-limb difference in moment distribution, and 3) if between-limb CoP_{pos} and ground reaction forces difference could predict between-limb knee extensor moment differences in individuals 4–5 months post-ACLR. It is hypothesized that more anterior CoP_{pos} during a squat will be related to smaller knee extensor moments relative to both hip extensor and ankle plantar flexor moments. When CoP_{pos} is considered relative to the non-surgical limb, it will be a strong predictor of between-limb differences in sagittal plane moment distribution. As a result of these relationships, between-limb CoP_{pos} ratio combine with between-limb GRF ratio will be a strong predictor to between-limb differences in knee extensor moments.

2. Methods

2.1 Participants

Twenty-four individuals (age: 28.9 ± 11.7 years; sex: 14 females, 10 males; height: 171.0 ± 10.8 cm; weight: 69.7 ± 11.8 kg) 4–5 months (142 ± 22.5 days) following ACLr participated in this study. Allograft ($n=9$) and bone–patellar tendon–bone ($n=11$) and hamstring ($n=4$) autograft procedures were performed by four different surgeons. Participants were included in the study if they were between the ages of 14–55, status-post ACLr and currently participating in physical therapy and excluded if they had a current injury to the contralateral limb that would influence function or a concurrent knee pathology that limited their weight bearing status. Data analyzed was collected as a part of a previous study that aimed to longitudinally assess lower extremity biomechanics following ACLr. Knee and hip extensor moments for 11 subjects were in the current data set that were published in a previous report (Sigward et al., 2018). Data from post-op month 5 from those subjects were considered along with additional participants who did not meet the longitudinal criteria from that study. Therefore, all data collected on individual 4–5 months post-ACLR that met the inclusion criteria were included to maximize sample size. No a priori sample size calculations were performed.

2.2 Procedures

Testing took place at the Human Performance Laboratory located in the Division of Biokinesiology and Physical Therapy. All procedures were explained to each subject and informed consent was obtained as approved by the University of Southern California's Institutional Review Board. Parental consent and youth assent were obtained for all subjects under the age of 18 years.

Due to a transition to a new motion capture system during the study, kinematic and kinetic data were collected using either an 11-camera motion capturing system (Qualysis Inc., Gothenberg, Sweden; 250 Hz) and force platforms (Advanced Mechanical Technologies, Inc., Newton, MA, USA; 1500 Hz) or a 14-camera motion capturing system (BTS Smart-DX motion capture system, BTS Bioengineering Corp., Milan, Italy; 340 Hz) and force platforms (BTS P-6000 DX, BTS Bioengineering Corp., Milan, Italy; 1360 Hz).

Prior to biomechanical testing, participants warmed-up on a stationary bike for 5 minutes. Reflective markers were placed bilaterally over the following anatomical landmarks: 1st and 5th metatarsal heads, medial and lateral malleoli, medial and lateral femoral epicondyles, greater trochanters, iliac crests, and a single marker on the joint space between the fifth lumbar and the first sacral spinous processes. In addition, marker clusters secured to rigid plates were placed bilaterally on the thighs, shanks, and heel counter of the shoes. A static calibration trial was collected with all markers attached. Marker clusters and markers on the foot and pelvis remained on throughout testing.

Participants performed squats with feet on individual force platforms, shoulder-width apart, and their arms crossed over their chest. No additional weight was added. They were instructed to squat down as low as possible without pain and return to the standing position between each squat. After practice, they performed 2 trials of 5 consecutive squats at a self-selected comfortable pace. A 3-minute break in between each trial was provided to prevent fatigue (Sigward et al., 2018).

2.3 Data Analysis

Marker coordinate data were labeled and digitized (Qualisys Track Manager, v2.8 or BTS Engineering Smart Tracker v1.10). Lower extremity kinematics and net joint moments were calculated using Visual3D™ (C-Motion, Inc., Rockville, MD, USA) software. Data were filtered using a fourth-order zero-lag Butterworth 12 Hz low-pass filter. Local coordinate systems of the pelvis, thighs, shanks and feet were derived from the standing calibration trial, and the six degrees of freedom of each segment was determined from marker clusters. Sagittal plane kinematics were calculated using a joint coordinate system approach (Grood and Suntay, 1983). Body mass was calculated using vertical vGRF during the static trial. Average vGRF (5 seconds) was divided by 9.81 m/s². Body mass, kinematics and GRF were used to calculate sagittal plane net joint moments at the knee and hip using standard inverse dynamics equations (Bresler and Frankel, 1950). Moments, reported as internal moments, were normalized to body mass.

A squat was defined as the time from standing (highest position of L5S1) to the next standing (highest position of L5S1). Hip and knee extensor as well as ankle plantar flexor

moments, and CoP_{pos} were determined at the time of peak vGRF. CoP_{pos} was calculated as the percentage distance of the foot length (%foot length) away from the heel on the longitudinal axis between toe and heel markers. Foot length was defined as the distance between markers placed over the second toe and posterior heel counter of the shoe. A greater number indicates a more anterior CoP_{pos} .

To characterize intra-limb sagittal plane joint moment distribution, ratios of hip to knee extensor moment (hEXT/kEXT) (Sigward et al, 2018) and ankle plantar flexor to knee extensor moment (aEXT/kEXT) were calculated for each limb. A ratio greater than 1 indicates that the hip extensor or ankle plantar flexor moment is greater than the knee extensor moment. A ratio less than 1 indicates that the knee extensor moment is greater than the hip or ankle extensor moment.

To characterize inter-limb difference in sagittal plane moment distribution relative difference between limbs in hEXT/kEXT and aEXT/kEXT were characterized by dividing the surgical limb ratios by the non-surgical limb ratios. A between limb ratio of greater than 1 for hEXT/kEXT_(SURG)/hEXT/kEXT_(NS) and aEXT/kEXT_(SURG)/aEXT/kEXT_(NS) indicates that the intra-limb moment distribution in surgical limb was more hip or ankle dominant, respectively than in the non-surgical limb. A ratio less than 1 indicates that the intra-limb moment distribution in surgical limb was more knee dominant than in the non-surgical limb. To characterize inter-limb difference in CoP_{pos} , vGRF and knee extensor moments between limb ratios (surgical/non-surgical) were calculated for each variable. All variables were averaged across three repetitions (middle three out of five repetitions) from two trials for each subject.

2.4 Statistical Analysis

Paired t-tests were used to establish the presence of between limb differences for all variables of interest. Separate simple linear regression analyses were used to determine the relationships between CoP_{pos} and sagittal plane joint moment distribution in each limb; hEXT/kEXT and aEXT/kEXT. Linear regressions were used to determine if the between-limb CoP_{pos} ratio was predictive of the between-limb ratio of hEXT/kEXT and aEXT/kEXT. Finally, stepwise linear regression was used to determine the independent predictive ability of between-limb COP ratio and vGRF of between-limb knee extensor moment ratio. The criterion ≤ 0.05 was used to enter a variable into the model, and the criterion probability of F-to-remove ≥ 0.10 was used to remove a variable from the model. Significance levels were set at $p = 0.05$. All analyses were performed using PASW Statistics (Chicago, IL, USA, v.18).

3. Results

Descriptive data are found in Table 1. CoP_{pos} differed between surgical and non-surgical limbs ($p=0.015$, $ES=0.37$; Table 1). On average, the CoP_{pos} in the surgical limb was 4% more anterior than the non-surgical limb. The hEXT/kEXT was greater in the surgical limb ($p=0.02$, $ES=1.28$; Table 1) and the aEXT/kEXT was greater in the surgical limb ($p<0.001$, $ES=0.088$; Table 1).

The linear regression analyses indicated that the CoP_{pos} predicted hEXT/kEXT ratio in the surgical ($R^2 = 0.51$, $p < 0.001$, $\beta = 0.71$, Figure 2A) and non-surgical limbs ($R^2 = 0.48$, $p < 0.001$, $\beta = 0.69$, Figure 2A). CoP_{pos} also predicted aEXT/kEXT ratio in the surgical ($R^2 = 0.38$, $p < 0.001$, $\beta = 0.62$, Figure 2B) and non-surgical limbs ($R^2 = 0.32$, $p < 0.001$, $\beta = 0.57$, Figure 2B).

The between-limb CoP_{pos} ratio predicted the between-limb ratio of hEXT/kEXT ($R^2 = 0.62$, $p < 0.001$, $\beta = 0.79$, Figure 3A). The between-limb CoP_{pos} ratio predicted the between-limb ratio of aEXT/kEXT ($R^2 = 0.31$, $p = 0.005$, $\beta = 0.56$, Figure 3B).

When between-limb ratios vGRF and CoP_{pos} were considered as independent variables to predict between-limb ratio in kEXT moments, CoP_{pos} ratio entered the equation first ($R^2 = 0.52$, $p < 0.001$, $\beta = -0.72$) followed vGRF ratio ($R^2 \text{ change} = 0.18$, $p = 0.002$). Together they explained 70% of the variance in kEXT ratio ($R^2 = 0.70$, $p < 0.001$, $\beta (\text{CoP}_{\text{pos}}) = -0.64$, $\beta (\text{vGRF ratio}) = 0.43$).

4. Discussion

The results of this study indicate that anterior/posterior position of the CoP is related to sagittal plane joint moment distribution during a squat in individuals following ACLr. As theorized, a more anterior position of the CoP_{pos} is related to a greater demand at the ankle and hip relative to the knee in the sagittal plane (Figure 1). Center of pressure position is more predictive of the within limb hEXT/kEXT ratio, explaining up to 51% of the variance versus explaining only 38% variance for aEXT/kEXT ratio. Larger within limb hEXT/kEXT and aEXT/kEXT ratios in the surgical compared to non-surgical limbs were expected as previous work has described intra-limb compensations that shift the demands away from the knee during squatting (Salem et al., 2003; Sigward et al., 2018). On average, intra-limb hEXT/kEXT ratio was 1.7 times greater in the surgical limb than non-surgical limb indicating that the surgical limb exhibited a strategy that relied more heavily on hip extensors versus knee extensors. To our knowledge, this is the first study to characterize a larger ankle plantar flexor relative to knee extensor moment distribution in the surgical limb. While the contribution from the knee extensors was generally greater than from the ankle plantar flexors for both limbs, the relative shift toward the ankle plantar flexors was 1.8 greater in the surgical limb. Despite the differences between the surgical and non-surgical limbs in intra-limb moment distribution, the relationship between intra-limb moment distributions and COP_{pos} were similar for each limb. This suggests that the relationship between these variables was not driven by presence of sagittal plane knee deficits in the surgical limb.

When considering between-limb differences in COP_{pos} and sagittal plane moment distribution a greater between-limb COP_{pos} ratio explains 62% of the variance in between-limb hEXT/kEXT ratio. By convention a larger between-limb COP ratio indicates a more anterior position in the surgical versus non-surgical limb; and, a larger between-limb hEXT/kEXT ratio indicates that the intra-limb moment distribution is more hip dominant in the surgical limb compared to the non-surgical limb. The strength of this relationship between COP_{pos} ratio and between-limb hEXT/kEXT ratio suggests that COP_{pos} may be used as a

proxy to identify the presence of compensations within the surgical limb during a squat exercise. While a greater between-limb COP_{pos} ratio is also related to a greater between-limb aEXT/kEXT ratio, it only explains 31% of the variance. As seen in Figure 3B, this relationship was driven by one individual who exhibited a larger between limb difference in aEXT/kEXT ratio. This data point was determined to be an outlier but the data reflected the strategy used by this individual and was not removed. If this individual was removed from analyses the prediction would have improved to 51%.

When considered along with between-limb differences in vertical ground reaction forces and between-limb differences in COP_{pos} predicted 70% of the variance in between-limb differences in knee extensor moments. In fact, COP_{pos} ratio was a stronger predictor than ground reaction force explaining 52% versus 18% of the variance in knee extensor moment ratio in this cohort. This has specific clinical implications for the identification and amelioration of compensatory strategies that reduce knee extensor moment demands during squatting. First, it strengthens the argument for utilization of instrumentation to quantify COP_{pos} along with force following ACLr. In fact, it suggests that while force measures provide important information about underloading during a squat, they alone, do not provide a complete picture. The early presence and long term persistence of knee extensor moment deficits during a simple squat task suggest that reeducation of loading patterns may be a critical part of rehabilitation. Reeducation that includes improving limb and knee loading is critical at 3 months post-ACLR as both inter and intra-limb compensations contribute to knee extensor moment deficits. (Sigward et al., 2018) The fact that similar reductions in knee extensor loading at 5 months are predicted only by shifts within the limb further supports the potential benefits of using COP_{pos} to identify intra-limb compensations. These compensations are difficult to observe clinically as they are present in the absence of large differences in joint angles. Identifying and addressing both types of compensations may be the key to mitigating their persistence later in rehabilitation. Validation of these procedures for predicting knee extensor moment deficits is needed to determine the clinical utility of these analyses.

Second, understanding that COP_{pos} is related to the distribution of demands within the limb may have value for exercise instruction. A more posterior position is related to a greater demand on the knee extensors. Recent work by Kitamura and colleagues suggests that an anterior shift of CoP_{pos} by approximately 30% in static squat positions with 30, 60 and 90 degrees of knee flexion results in substantial changes in muscle activation that favor the hip extensors and ankle plantar flexors. (Kitamura et al., 2019) However, it is not clear if instructing individuals following ACLr to shift their COP posteriorly would change knee extensor moments. Given that there is considerable overlap in COP location between limbs (Sx range: 35–77%, NS range: 31–69% of foot length) and an average difference between limbs of only 4% of foot length, instructions to move the COP more posterior may not be effective. Using the non-surgical limb COP as a reference may be a more effective target for a subtle change. However, it is not known if individuals are capable of identifying between limb differences in COP position or if changes to position will reduce compensations or result in different compensatory strategies.

Application of these data for clinical identification of compensatory strategies is limited to the task evaluated. The relationship between COP_{pos} and moment distribution cannot be assumed in tasks that do not require full and constant foot contact on the floor (i.e. landing) or tasks that are performed on a single limb task. Interpretation of these data is limited to individuals between 3 and 5 months post-surgery. It is not known if these relationships would be found at earlier or later time points in rehabilitation. While strong relationships exist, the ability to use these analyses for clinical prediction of knee extensor moment deficits during a bilateral squat is not known. Analysis of a larger sample size that includes individuals across time points during rehabilitation is needed. The range in the ages of these participants limits our ability to extrapolate these findings to specific post-operative age groups. Caution should be taken when applying this information to exercise instruction. COP position may only reflect what is happening in the limb and may not influence sagittal plane loading distribution.

5. Conclusions

During a bilateral squat task, center of pressure position is predictive of intra-limb sagittal plane moment distribution. A more anterior center of pressure position is related to relatively higher demands at the hip and ankle compared to the knee. This relationship is strong when considering intra-limb compensations between the knee and hip in individuals following ACLr. Between-limb differences in center of pressure location explain 62% of the variance in between-limb differences in hip to knee sagittal plane moment distribution. Between-limb differences in center of pressure along with between-limb differences in vertical ground reaction forces predict 70% of the variance in between-limb differences in knee extensor moments. These two force plate derived metrics may allow for improved identification of inter- and intra-limb compensations in individuals following ACLr.

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Diagram of resultant ground reaction force (GRF) from two center of pressure (COP) positions. Solid circles represent axes of rotation for sagittal plane motion at the hip, knee and ankle. The dashed line and X represent a more anterior COP. Theoretically, this places the GRF trajectory closer to the knee joint center and farther from the hip and ankle joint centers; resulting in a smaller moment arm for the external force and smaller demand at the knee with larger moment arms at the hip and ankle when compared to the solid line and X.

Figure 2:

Relationship between center of pressure position and within limb distribution of extensor moments between the hip and knee (A) and ankle and knee (B) for each limb

Figure 3:
Relationship between between-limb CoP_{pos} ratio and between-limb ratio of hEXT/kEXT
(A) and aEXT/kEXT (B)

Table 1.

Kinetic and COP position variables between surgical and Non-surgical limbs: Mean (standard deviation)

	Surgical	Non-surgical	Mean Difference	95% Confidence Interval	
				Lower	Upper
Peak knee extensor moment (Nm/kg)	-0.79 (.020)	-1.18 (0.19)	0.39 * (0.21)	0.30	0.47
COP _{pos} ^{‡‡} (% foot length)	55.55 (13.04)	51.20 (10.59)	4.35 [‡] (8.14)	0.91	7.79
Vertical GRF [‡] (N)	432.16 (89.58)	494.38 (116.72)	-62.22 [‡] (49.31)	-83.05	-41.40
hEXT/kEXT [‡]	1.51 (0.68)	0.88 (0.30)	0.63 [‡] (0.53)	0.41	0.86
aEXT/kEXT [‡]	0.51 (0.35)	0.28 (0.17)	0.23 [‡] (0.28)	0.11	0.35

COP_{pos}= Center of pressure position from heel, GRF= ground reaction force, hEXT/kEXT= hip extensor moment/knee extensor moment ratio, aEXT/kEXT =ankle plantarflexor moment/ knee extensor moment ratio.

* significant differences p<0.015

[‡] significant differences p<0.0001

^{‡‡} variable identified at the time of peak knee extensor moment.