Relationships Between Knee Extension Moments During Weighted and Unweighted Gait and Strength Measures That Predict Knee Moments After ACL Reconstruction

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Background: Weighted gait increases internal knee extension moment impulses (KEMI) in the anterior cruciate ligament–reconstructed (ACLR) limb; however, limb differences persist.

Hypotheses: (1) KEMI during normal gait will influence KEMI during weighted gait and (2) peak knee extension (PKE) torque and time to reach PKE torque will predict KEMI during gait tasks.

Study Design: Descriptive laboratory study.

Methods: Twenty-four women and 14 men completed 3 gait tasks (unweighted, vest, sled) and strength testing after discharge from rehabilitation and clearance to return to sports. KEMI were calculated during the first 25% of stance. PKE torque and time to reach PKE torque were obtained using a dynamometer. Data on the ACLR limb and symmetry indices (SIs) were analyzed for each sex.

Results: Women presented with asymmetrical PKE torques and KEMI across tasks. There were three correlations noted for KEMI: between the walk and vest, walk and sled, and vest and sled tasks. Slower time to PKE torque predicted limb asymmetries across tasks and KEMI in the ACLR limb during the sled task. Men presented with asymmetrical PKE torques and KEMI during the sled task. There was a correlation noted for KEMI between walk and vest tasks only. During the sled task, ACLR limb time to PKE torque predicted KEMI in the ACLR limb and PKE torque SI predicted KEMI SI.

Conclusion: Women use asymmetrical KEMI profiles during all gait tasks, and those with worse KEMI during walking have worse KEMI during weighted gait. Men have asymmetrical KEMI when sled towing, and these KEMIs do not correlate with KEMI during walking or vest tasks.

Clinical Relevance: PKE torque deficits persist when attempting to return to sports. Only men use gains in PKE torque to improve KEMI profiles. Although quicker PKE torque generation will increase KEMI in women, normalization of KEMI profiles will not occur by increasing rate of force development only. Gait retraining is recommended to correct asymmetrical KEMI profiles used across gait tasks in women.

Keywords: quadriceps strength; gait; return to sport; internal knee extension moment

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Many who experience an anterior cruciate ligament (ACL) rupture opt for ACL reconstruction (ACLR),[8,32,33] yet reduced internal knee extension moments (KEM) during gait[13,14] and long-term strength deficits[2,29,34,39,41,44] may continue. Reduced KEM during the weight acceptance phase of gait (eg, loading response) is ubiquitous after ACL injury[9,46] and may persist postoperatively.[15] Reduced KEM leads to poor functional outcomes[4-6,31,36,40,51] and may increase risk of rerupture.[38] Determining whether reduced KEM profiles persist during the loading response across different gait tasks is necessary to guide interventions. Identifying muscle performance measures that are most predictive of reduced KEM during gait will inform which strength deficits to address to increase KEM after ACLR.

Individuals post-ACLR as well as healthy individuals[30,49] increase KEM throughout loading response (eg, first 25% of stance) while towing a weighted sled and wearing a weighted vest loaded with 50% body weight (BW) compared with unweighted gait.[20] Significant increases in KEM in the ACLR limb during weighted gait with 50% BW are encouraging given that 20% BW did not significantly increase KEM in the ACLR limb.[20] Though towing a sled and wearing a weighted vest with 50% BW increased KEM in the ACLR limb, KEM was significantly less than that in the uninvolved limb for all tasks in both women and men.[20] This asymmetry may negatively affect successful outcomes when attempting to return to sports.[15] Thus, the potential benefits of using weighted gait as an intervention to increase KEM after ACLR is unclear.

Knowledge of muscle performance measures that best predict KEM profiles would also guide best practice. Impaired peak knee extension (PKE) torque (impaired quadriceps strength) continues after ACLR[12,28,34,37,39,41,47,52] and limits the ability to return to previous levels of activity.[11,13,17,22,23,26,35,48] Asymmetrical PKE torque coincides with aberrant KEM during gait after ACLR.[31,45] Though deficits in PKE torque are common after ACLR,[12,18,28,34,37,39,41,47,52] PKE may provide limited information about muscle performance during dynamic tasks.[16,35] Time to generate PKE torque has potential to add unique contributions to KEM profiles.[3,53] Perhaps PKE torque and time to generate PKE torque combined will best predict KEM in the ACLR limb and/or KEM limb symmetry during gait.

Sled towing and wearing a weighted vest create unique demands on KEM impulses (moment over time), specifically the first 25% of the stance phase of gait.[30] The knee extends to propel the body forward during the loading phase of sled towing. Conversely, the knee flexes as the limb accepts load when wearing a weighted vest. Perhaps muscle performance variables that predict KEM during a gait task that requires a concentric quadriceps contraction differ from a gait task that requires an eccentric contraction.

The purposes of this study were 3-fold. First, to describe KEM impulses (KEMI) and muscle performance profiles in the ACLR limb and calculate symmetry indices (SIs) to illustrate how the ACLR limb compares with the uninvolved limb in individuals who were discharged from rehabilitation and cleared to return to sports. Second, to determine whether the KEMI in the ACLR limb during unweighted gait influences KEMI in the ACLR limb during weighted gait and whether KEMI SIs during unweighted gait influence KEMI SIs during weighted gait. Thirdly, to determine whether PKE torque and time to PKE torque predict KEMI profiles (ie, ACLR limb and SI) during gait tasks (ie, walk, sled, vest).

METHODS

Participants

This study was approved by the University of New England's Institutional Review Board. This was a secondary analysis of previously published data.[20] Given the exploratory nature of this secondary analysis, no prior power analysis was completed. The parent study demonstrated that 24 women and 14 men had significantly increased KEMI when gait was weighted compared with unweighted gait, yet significant limb differences regarding KEMI persisted across weighted and unweighted gait tasks.[20] Men and women were analyzed separately to remove the influence of sex on gait mechanics.[7,14,19]

Individuals were eligible for the study if their growth plates were closed, ACLR had occurred in the past 5 to 12 months, they were discharged from physical therapy, and were cleared to return to sports. While achieving return to sports status at 5 months is atypical,[21] this time frame was chosen to capture individuals who were cleared to return to sports but had not fully integrated back to sports participation. Individuals were excluded if they had concomitant knee ligament injury during ACL rupture, known cardiac or neurologic pathology, surgery within 12 months excluding ACLR, knee pain with activity, current use of pain medication, or ACL revisions.

Demographic data were collected (Table 1) after the individuals gave written informed consent. Normal walking trials were collected first, then the order of the weighted gait tasks (sled and vest) was randomized (Figure 1). Motion and ground-reaction force data were collected during stance phase of gait using 8 Series 3 cameras (Qualisys) and 2 force plates (AMTI).[20] Collection rates and data processing are described in a previous publication.[20] Visual 3D software (C-motion) was used to calculate KEMI (N·m·s/kg) during the first 25% of stance phase. On completion of the gait trials, muscle performance measurements were collected using an isokinetic dynamometer (Biodex S4 Medical Systems). Hip flexion was set at approximately 90° with the individual's trunk fully supported, arms crossed at the chest, and straps firmly secured at the waist, thigh, and distal lower extremity. Verbal and visual feedback were provided to encourage maximum effort.

First, isometric PKE torque testing was performed with the knee at 90° of flexion. Three trials of maximum voluntary isometric quadriceps contractions were performed on each limb, with a 120-second rest break between each 3-second trial. For isokinetic testing, the individual performed 10 concentric knee extension and 10 concentric knee flexion contractions at an angular velocity of 60 deg/s[16,41] between 0° and 90° of knee

Table 1. Participant demographics

	Women (n = 24)	Men (n = 14)
Age, y, mean (SD)	25.0 (10.8)	23.9 (12.1)
Body mass index, kg/m^2, mean (SD)	23.7 (3.9)	24.9 (4.1)
Time since surgery, mo, mean (SD)	7.2 (1.8)	7.9 (1.9)
Meniscus injury concurrent with ACL injury, n	11	9
Contact injury, n	6	8
Noncontact injury, n	18	6

ACL, anterior cruciate ligament.

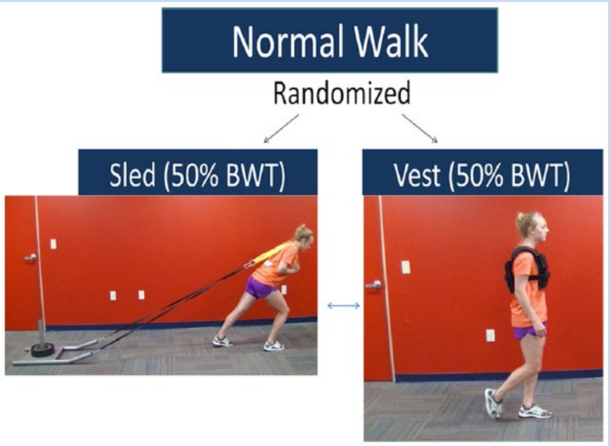

Figure 1. Weighted gait tasks utilized in this study: sled (EliteFTS) and vest (V-Max). BWT, body weight.

flexion.[43] Isokinetic variables include PKE torque and time to PKE torque. The torque data were normalized to body weight.

SIs were calculated to describe the ACLR limb relative to the uninvolved limb: SI = [(Variable$_{\text{ACLR limb}}$ / Variable$_{\text{uninvolved limb}}$) × 100]. Thus, SI values greater than 100% indicate that the ACLR limb was better than the uninvolved limb, except for time to PKE torque, as SI values greater than 100% indicate that the ACLR limb is worse (eg, delayed time to reach PKE torque). Clinically meaningful asymmetry was operationalized as an SI value of less than 85% for KEMI or greater than 115% for time to generate PKE torque.

Statistical Analyses

Statistical analyses were completed using SPSS version 21 (IBM Corp). Pearson product-moment correlations were performed to determine associations among the ACLR limb KEMI for the walk, vest, and sled tasks and then among the KEMI SIs for the 3 gait tasks. Correlations were performed between the independent (eg, muscle performance variables) and dependent (ie, ACLR limb KEMI and KEMI SI for each gait task) variables. Further correlations were conducted to assess whether time since surgery to data collection influenced any independent or predictor variable. Stepwise linear regressions were performed by adding all independent variables that significantly correlated ($P \leq 0.05$) with the respective dependent variable.[42] The significance for the stepping method criteria was set at $P \leq 0.05$ for entry into and $P \leq 0.10$ for removal from the model.

RESULTS

Women

All 3 KEMI SIs and 2 of the 3 muscle performance measures met the definition of limb asymmetry for women (Table 2). The KEMIs were significantly positively correlated between walk and vest, walk and sled, and vest and sled tasks for both the ACLR limb and SI (Table 3). Time since surgery did not correlate with any gait variable or muscle performance measures used in the linear regression.

Time to PKE torque SI significantly correlated with and predicted KEMI SI during the walk task (Tables 4 and 5, respectively), ACLR limb time to PKE torque significantly correlated with and predicted ACLR limb KEMI during the sled task (Table 4 and 5, respectively), and ACLR limb time to PKE torque and time to PKE torque SI significantly correlated with the KEMI SI during the sled task (Table 4). Of the 2 potential predictors, only ACLR limb time to PKE torque predicted KEMI SI during the sled task (Table 5). ACLR limb time to PKE torque significantly correlated with and predicted KEMI SI during the vest task (Table 4 and 5, respectively). There were no correlations between any muscle performance measures and the ACLR limb KEMI during the walk or vest tasks (Table 4), thus there were no potential predictors (Table 5).

Men

One of 3 KEMI SI variables and all 3 muscle performance measures met the definition of limb asymmetry for men (Table

Table 2. KEMIs and muscle performance variables for ACLR limb and SIs for women and men[a]

	Women		Men	
	ACLR Limb	SI	ACLR Limb	SI
Walk KEMI (N·m·s/kg)	0.03 (0.02)	**79.1 (27.4)**	0.04 (0.01)	92.84 (27.3)
Sled KEMI (N·m·s/kg)	0.09 (0.03)	**72.3 (19.4)**	0.08 (0.02)	**83.30 (23.7)**
Vest KEMI (N·m·s/kg)	0.05 (0.02)	**79.8 (29.7)**	0.07 (0.03)	92.4 (32.1)
Isometric PKE torque (%BW)	68.0 (18.0)	**67.6 (17.7)**	98.1 (25.7)	**73.7 (11.8)**
PKE torque (%BW)	57.8 (13.1)	**73.6 (13.1)**	75.6 (15.1)	**84.9 (23.3)**
Time to PKE torque (ms)	567.5 (151.9)	114.7 (22.8)	510.0 (80.9)	**124.4 (39.3)**

ACLR, anterior cruciate ligament reconstruction; BW, body weight; KEMI, knee extension moment impulse; PKE, peak knee extension; SI, symmetry index.
[a]Data presented as mean (SD). Boldfaced values indicate limb asymmetries.

Table 3. Correlations among the internal knee extension moments for the anterior cruciate ligament–reconstructed (ACLR) limb and symmetry index (SI)

	Women		Men	
	ACLR Limb	SI	ACLR Limb	SI
Walk and vest tasks				
r	0.721[b]	0.553[b]	0.602[a]	0.622[a]
P	<0.001	0.005	0.023	0.017
Walk and sled tasks				
r	0.610[b]	0.539[b]	0.499	0.015
P	0.002	0.007	0.069	0.961
Vest and sled tasks				
r	0.543[b]	0.702[b]	0.334	0.210
P	0.006	<0.001	0.244	0.470

[a]$P < 0.05$.
[b]$P < 0.01$.

2). The KEMI during the walk task was significantly correlated with the vest task for both the ACLR limb and SI (Table 3). Time since surgery did not correlate with any gait variable or muscle performance variables used in the linear regression.

ACLR limb time to PKE torque significantly correlated with and predicted ACLR limb KEMI during the sled task (Tables 6 and 7, respectively), and ACLR limb PKE torque and PKE torque SI significantly correlated with KEMI SI during the sled task (Table 6); however, only PKE torque SI significantly predicted KEMI SI during the sled task (Table 7). There were no correlations between the muscle performance measures and the ACLR limb KEMI or SI during the walk or vest tasks (Table 6), thus there were no potential predictors (Table 7).

DISCUSSION

Findings of asymmetrical PKE torques and KEMI during all gait tasks for women and sled task for men illustrate continued

Table 4. Correlations between knee extension moments and muscle performance data in women

	Walk KEMI		Sled KEMI		Vest KEMI	
	ACLR Limb	SI	ACLR Limb	SI	ACLR Limb	SI
ACLR limb isometric PKE torque						
r	0.227	–0.132	0.269	0.050	0.036	–0.264
P	0.286	0.539	0.204	0.815	0.869	0.212
Isometric PKE torque SI						
r	0.210	0.015	0.231	0.110	–0.064	–0.236
P	0.326	0.944	0.277	0.608	0.765	0.267
ACLR limb PKE torque						
r	0.004	–0.019	–0.047	0.146	–0.197	–0.088
P	0.986	0.930	0.828	0.497	0.357	0.684
PKE torque SI						
r	0.329	0.152	0.288	0.379	0.068	0.047
P	0.116	0.478	0.173	0.068	0.751	0.826
ACLR limb time to PKE torque						
r	–0.346	–0.230	–0.477[a]	–0.560[b]	–0.251	–0.489[a]
P	0.098	0.279	0.018	0.004	0.237	0.015
Time to PKE torque SI						
r	–0.268	–0.406[a]	–0.155	–0.455[a]	–0.093	–0.350
P	0.206	0.049	0.469	0.025	0.665	0.093

ACLR, anterior cruciate ligament reconstruction; KEMI, knee extension moment impulse; PKE, peak knee extension; SI, symmetry index.
[a] $P < 0.05$.
[b] $P < 0.01$.

Table 5. Predictors of KEMI profiles in women

Dependent Variable		Predictor Variable	*P*	Standardized Coefficients Beta	Adjusted R^2
Walk KEMI	ACLR limb	N/A			
	SI	Time to PKE torque SI	0.049	–0.406	0.127
Sled KEMI	ACLR limb	ACLR limb time to PKE torque	0.018	–0.477	0.193
	SI	ACLR limb time to PKE torque	0.004	–0.560	0.282
Vest KEMI	ACLR limb	N/A			
	SI	ACLR limb time to PKE torque	0.015	–0.489	0.204

ACLR, anterior cruciate ligament reconstruction; KEMI, knee extension moment impulse; N/A, not applicable; PKE, peak knee extension; SI, symmetry index.

Table 6. Correlations between knee moments and muscle performance data in men

	Walk KEMI		Sled KEMI		Vest KEMI	
	ACLR Limb	SI	ACLR Limb	SI	ACLR Limb	SI
ACLR limb isometric PKE torque						
r	0.090	0.047	0.413	0.522	0.451	0.305
P	0.761	0.873	0.142	0.055	0.105	0.288
Isometric PKE torque SI						
r	–0.058	–0.039	0.076	0.281	0.392	0.328
P	0.843	0.895	0.797	0.331	0.166	0.252
ACLR limb PKE torque						
r	0.057	0.065	0.476	0.565[a]	0.215	0.176
P	0.846	0.825	0.085	0.035	0.460	0.548
PKE torque SI						
r	0.335	–0.296	0.292	0.708[b]	0.339	0.078
P	0.242	0.305	0.312	0.005	0.236	0.791
ACLR limb time to PKE torque						
r	–0.020	0.382	–0.548[a]	–0.471	0.156	0.218
P	0.945	0.178	0.043	0.089	0.595	0.454
Time to PKE torque SI						
r	–0.143	0.288	–0.467	–0.165	–0.323	–0.033
P	0.625	0.318	0.092	0.572	0.260	0.911

ACLR, anterior cruciate ligament reconstruction; KEMI, knee extension moment impulse; PKE, peak knee extension; SI, symmetry index.
[a] $P < 0.05$.
[b] $P < 0.01$.

Table 7. Predictors of KEMI profiles in men

Dependent Variable		Predictor Variable	*P*	Standardized Coefficients Beta	Adjusted R^2
Walk KEMI	ACLR limb	N/A			
	SI	N/A			
Sled KEMI	ACLR limb	ACLR limb time to PKE torque	0.043	–0.548	0.242
	SI	PKE torque SI	0.005	0.708	0.460
Vest KEMI	ACLR limb	N/A			
	SI	N/A			

ACLR, anterior cruciate ligament reconstruction; KEMI, knee extension moment impulse; N/A, not applicable; PKE, peak knee extension; SI, symmetry index.

aberrant gait patterns and strength deficits despite ACLR and rehabilitation. Significant relationships in KEMI profiles between unweighted and weighted gait are novel findings. Moderate correlations (eg, $r > 0.50$)[10] among KEMI in women suggest that aberrant KEMI used during normal gait influences KEMI when gait is weighted. Conversely, men's aberrant KEMI profiles when towing the sled are not related to KEMI during normal gait. Interestingly, time to PKE torques predicted KEMI profiles for women, whereas PKE torques predicted KEMI during the sled task for men. These findings have clinical implications, as asymmetrical KEMIs during gait result in poorer functional outcomes.[15]

In women, PKE torque deficits do not translate to KEMI deficits; furthermore, greater PKE torques do not result in greater KEMI during gait tasks. Instead, if women take longer to reach peak quadriceps torque in the ACLR limb, then KEMI profiles are more asymmetrical. However, interventions solely to address faster time to PKE torque in women will not likely result in clinically meaningful changes in KEMI profiles. Given the large magnitude of limb asymmetries in KEMI profiles and the relationship of KEMI profiles across the 3 gait tasks, gait retraining is likely needed to restore KEMI profiles in women after ACLR. Although quicker torque development may not normalize KEMI, negative implications of slower torque development have been reported,[1,3,24,25,27,29,50] suggesting other potential benefits of quickly generating knee extension torque after ACLR.

Given that men achieved a large increase in KEMI during the weighted vest task without incurring asymmetrical KEMI profiles (Table 2), using a weighted vest to increase KEMI in the ACLR limb[20] may be beneficial in men. Additionally, a large portion of the variance (46%) in KEMI symmetry when towing a sled was explained by PKE torque symmetry in men. Thus, maximizing quadriceps force in the ACLR limb in men may restore symmetrical PKE torque as well as gait symmetry when towing a sled.

Limitations

The small sample size increases risk of statistical error and limits our ability to find true relationships. The amount and type of physical therapy, individual's compliance level with therapy, and type of ACLR were not controlled. Whether interventions to address strength deficits, rate of force development, or gait deviations occurred are unknown. Lasting effects of using weighted gait tasks after ACLR cannot be inferred from this study.

CONCLUSION

Limb asymmetries (eg, knee moments and strength profiles) are clinically concerning given that individuals were discharged from physical therapy and cleared to return to sports. Women who present with greater gait deviations during normal gait also use this more pronounced aberrant KEMI profile during weighted gait tasks. Gait retraining intended to directly increase KEMI in the ACLR limb and create symmetrical KEMI profiles appears necessary in women given the magnitude of asymmetry and persistent aberrant patterns used across gait tasks. Men present with aberrant KEMI profiles while towing a sled and have potential to correct KEMI profiles by maximizing quadriceps torque in the ACLR limb.

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