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# Lower extremity joint moments throughout gait at two speeds more than 4 years after ACL reconstruction

Karine Josibel Velasques Stoelben[a,*], Evangelos Pappas[b], Carlos Bolli Mota[c]

[a] Federal University of Pampa - Laboratory of Applied Neuromechanics, BR 472 km 592 - Po box 118 - ZIP 97500-970, Uruguaiana, RS, Brazil
[b] The University of Sydney, Faculty of Health Sciences, 75 East str, Lidcombe, NSW 2141, Australia
[c] Federal University of Santa Maria, Laboratory of Biomechanics, 1000 Roraima Avenue, building 51, room 1007, ZIP: 97105-900, Santa Maria, RS, Brazil

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ABSTRACT

*Background:* Long-term gait adaptations after anterior cruciate ligament reconstruction (ACLR) have been reported. However, it is still unclear if they persist more than 4 years after surgery and if they are affected by gait speed.

Research question: To investigate differences between groups, legs and walking speeds for ankle, knee and hip joint moments in three planes throughout the stance phase of gait.

*Methods:* Reconstructed participants (n = 20 males, 32.5 years, 5.5 years post-ACLR) and healthy controls (n = 20 males, 30.6 years) took part in the study. Gait analysis was performed in two different speeds (self-selected and 30% faster). Sagittal, frontal and transverse plane external moments were measured for ankle, knee and hip and compared throughout the stance phase using 95% confidence intervals. Significant differences were established as a consecutive 5% of gait cycle in which 95% confidence interval did not overlap.

*Results:* The reconstructed leg did not demonstrate higher joint moments; there were largely no differences while there was lower knee external rotation moment compared to the non-preferred leg of the control group. Higher joint moments were observed during fast speed walking on sagittal plane for knee and hip moments in both groups, and in the frontal and transverse plane for ankle moments.

*Significance:* Gait kinetics appear to be largely normalized at a minimum of 4 years after ACLR. Faster walking speed increase lower extremity joint moments.

## 1. Introduction

The rupture of anterior cruciate ligament (ACL) is one of the most frequent knee lesions in recreational activities and sports [1,2]. For physically active individuals, the most common treatment option is ACL reconstruction (ACLR) [3]. In Brazil, the number of ACLR performed in the Brazilian Unified Healthy System has increased by 64% from 2008 to 2014 with 82% of the procedures performed on men [4]. The goals of ACLR are to decrease symptoms, improve function, and return patients to their preinjury level of activity [5]. However, only about 65% of individuals return to their previous level of activity [6] and it is estimated that approximately 20 to 25% will have a second knee injury [7].

Movement asymmetries persist for several years after ACLR. Recent systematic reviews demonstrate that ACLR does not completely restore normal knee joint gait biomechanics [8,9]. In the sagittal plane, knee flexion angles tend to normalize over time (up to 6 years) after ACLR, however it remains unclear if joint moments are asymmetrical more than 3 years after ACLR [8,9]. There are conflicting results for the frontal plane moments. Kaur et al. [9] reported peak knee adductor moments were lower in ACLR participants than in controls (up to 3.5 years post ACLR) and increase as time following reconstruction progresses (more than 3.5 years). However, Hart et al. [8] reported that ACLR individuals had similar knee adductor moments compared to healthy controls and contralateral knees (more than 3.0 years after surgery). In the transverse plane, while it appears that abnormal biomechanics are evident after ACLR, limited studies presented transverse plane biomechanical variables, so it is unclear which long-term adaptations occur in this plane post-ACLR [8,9].

Walking is one of the most common repetitive functional activities, that humans perform on a daily basis [10]. It is recommended as a form of exercise for people who are beginning physical fitness programs or recovering from musculoskeletal injuries [11], and increasing walking speed is a form for incremental workout intensity [11]. Increase sagittal and frontal plane joint moments have been reported with increase in

* Corresponding author.
*E-mail addresses:* karinestoelben@gmail.com (K.J.V. Stoelben), evangelos.pappas@sydney.edu.au (E. Pappas), bollimota@gmail.com (C.B. Mota).

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walking speed in healthy male individuals [11] and individuals with osteoarthritis [12]. However, it is unclear if different compensations occur in ACLR individuals when walking speed is increased.

Biomechanical gait analysis frequently assesses peak moments which may fail to capture differences that occur at other parts of the gait cycle. Analysis throughout the entire stance phase can identify segment of the gait cycle that need more careful attention during training and rehabilitation programs. However, only one study has analyzed joint moments during gait after 3 years of ACLR [13]. Thus, the primary aim of this study was to compare ankle, knee and hip joint moments in three planes throughout the stance phase of the gait cycle between individuals who have undergone ACLR and healthy controls. The secondary aim was to identify differences between the reconstructed and uninjured leg of the ACLR group and between walking speeds. It was hypothesized that the reconstructed leg of ACLR individuals will have higher lower extremity moments than healthy controls and the uninjured leg and that increased walking speed will increase joint moments in general for both groups.

## 2. Methods

### 2.1. Participants

Forty men between 25 and 45 years old took part in the study. Twenty of them had complete unilateral ACL rupture with no-contact mechanism of injury followed by reconstruction with autograft (patellar tendon or hamstring tendon) between 48 and 96 months prior to testing (ACLR group), had participated in a post-ACLR rehabilitation program, and had no other history of serious lower limb injury (re-injury in the same joint, injuries in any other joint that may have affected gait) or neurological injury or body mass index higher than 35.0 kg/m$^2$. The control group consisted of 20 men who did not have any joint, muscular or neurological lower limb pathology and were matched to the ACLR group with respect to physical activity level, height and weight. Both groups were samples of convenience and were recruited by advertisements in the university site and local social media. Participant characteristics are provided in Table 1.

Ethical clearance was obtained by the Research Ethics Committee of local institution (CAAE nº: 26,928,514.6.0000.5346). All participants were informed of the benefits and risks of the investigation prior to signing an institutionally approved informed consent document.

**Table 1**
Participant characteristics presented in mean (SD) or number [%].

| Characteristic | | Group | |
|---|---|---|---|
| | | ACLRG (n = 20) | CG (n = 20) |
| Age (years) | | 32.5 (5.8) | 30.6 (6.8) |
| Body mass (kg) | | 84.9 (12.4) | 83.2 (12.0) |
| Height (cm) | | 175.9 (7.2) | 178.2 (6.7) |
| Baecke activity level score | | 8.3 (1.1) | 8.0 (1.3) |
| Self-selected walking speed (m/s) | | 1.37 (0.18) | 1.41 (0.16) |
| Fast walking speed (m/s) | | 1.78 (0.18) | 1.81 (0.19) |
| Preferred limb | Right | 15 [75%] | 16 [80%] |
| | Left | 3 [15%] | 3 [15%] |
| | Ambidextrous | 2 [10%] | 1 [5%] |
| IKDC (score) | | 83.3 (14.4) | NA |
| KOOS (score) | Symptoms | 82.0 (13.6) | NA |
| | Pain | 87.2 (11.2) | NA |
| | ADL | 93.7 (8.5) | NA |
| | Sport | 80.3 (15.3) | NA |
| | QOL | 68.8 (21.2) | NA |
| Reconstructed limb (right) | | 12 [60%] | NA |
| Autograft (patellar) | | 10 [50%] | NA |
| Time since surgery (months) | | 66.9 (15.9) | NA |

IKDC: International Knee Documentation Committee; KOOS: Knee Injury and Osteoarthritis Outcome Score; NA: not applicable; ADL: activities of daily living; QOL: knee-related quality of life. IKDC and KOOS scores vary from 0 to 100, where higher scores indicate better knee function.

### 2.2. Measurements

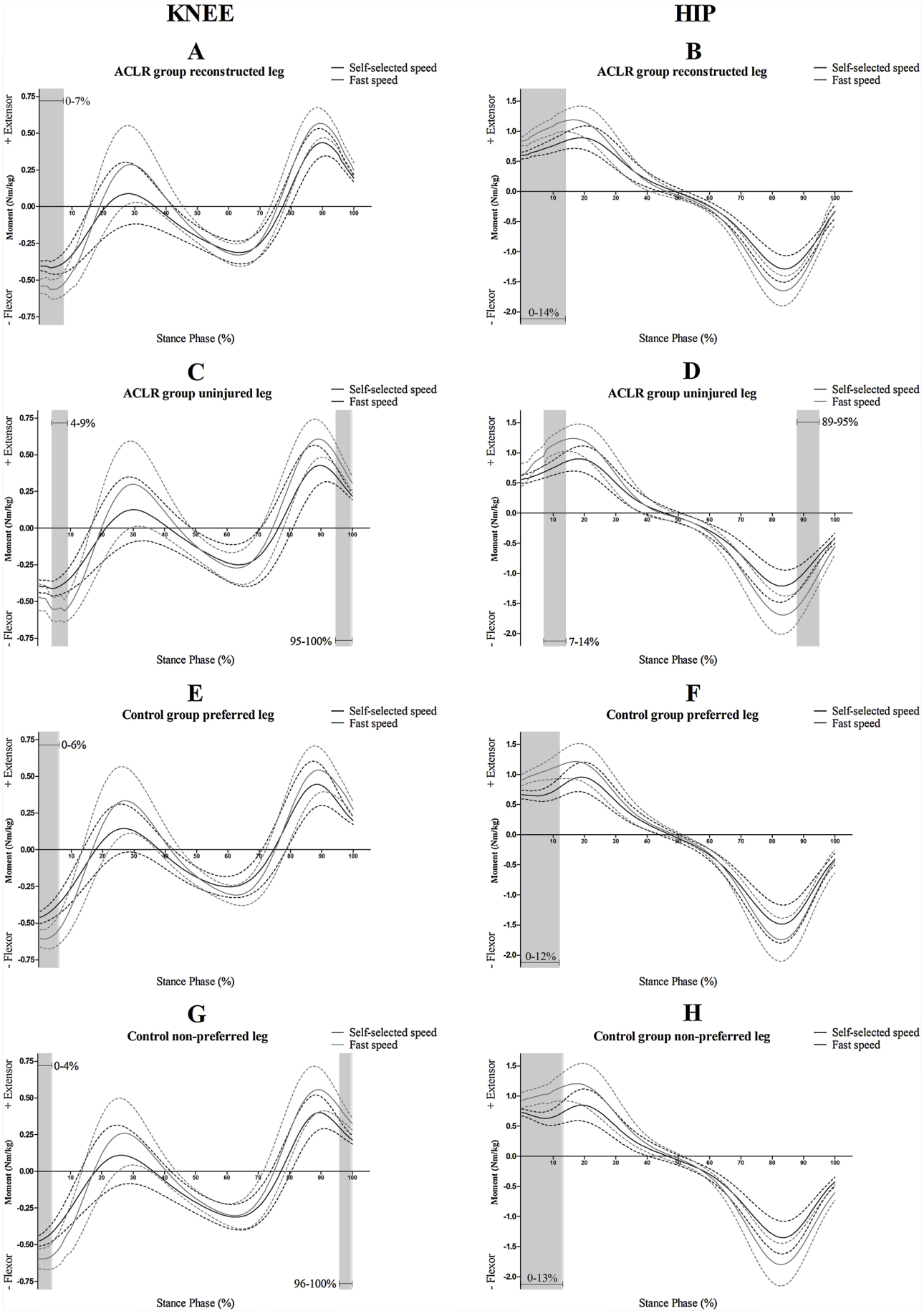
Questionnaires were completed before the measurement of gait biomechanics. The Baecke (physical activity) and Waterloo Footedness (WFQ-R) (lower limb preference) questionnaires were completed by both groups. The Baecke physical activity score was assessed according to Florindo et al. [14], the score variation is between 3 and 15, with higher values indicating higher level of activity. The WFQ-R score included the categories left-always, left-usually, equal, right-usually and right-always on a scale from 0 to 10 for each question. The total score was the sum of individual question scores. The lower limb preference was defined with values higher than 55 indicating right preference, between 55-45 ambidextrous and lower than 45 left preference. The Knee Injury and Osteoarthritis Outcome Score (KOOS) and International Knee Documentation Committee (IKDC) were completed by the ACLR group to assess knee health. Higher scores (out of 100) indicate higher knee function.

The gait trials started after measurement of body mass and height. Then, a marker set was placed on participants according to the Vicon PlugInGait model by the same researcher. Sixteen markers were placed on the anterior and posterior superior iliac spines, lateral thigh, lateral femoral epicondyle, lateral shank, calcaneus, lateral malleolus and second metatarsal head for both sides. The markers were fixed using double-side adhesive tape. Seven infrared cameras (VICON system, 624 model, Oxford, United Kingdom) captured the motion with acquisition frequency set at 200 Hz. Two force plates (AMTI OR6-6-2000, Watertown, MA, EUA) recorded kinetic data at 1000 Hz. Kinematic and kinetic data were collected using VICON Nexus software (Version 1.5.3). Walking speed was assessed by tracking the average velocity of the hip marker (right anterior superior iliac spine marker). To obtain a reference point for the markers, a static trial was obtained with the subject in quiet standing for approximately 3 s. Participants were instructed to walk barefoot on a 10 m walkway at two different speeds: their self-selected walking speed and 30% faster than the preferred speed (maintained within ± 5% to be considered as an acceptable trial for each condition). Participants were not aware of the location of the force plates that were concealed. Any trials in which there were not two consecutive foot strikes onto the force plates were discarded. Three gait cycles for each leg, in which two full foot strikes onto the force plates were detected and with walking speed was maintained within ± 5% at each speed condition, were saved.

### 2.3. Data analysis

The data were analyzed for the stance phase of the gait cycle, with initial contact of the foot at 0% and the foot off at 100%. A 10 N threshold was used to determine initial contact and toe-off. Kinematic and kinetic data were filtered by a 4th order zero-lag Butterworth low pass filter, with cut-off frequency of 6 Hz (determined by Winter [15] residuals criteria). Joint moments were calculated with inverse dynamics equations of motion by Vicon Plug In Gait Model and were normalized to body weight, they were also filtered by the same filter and cut-off frequency of kinematic and kinetic data.

For each walking speed we compared legs between groups and legs within each group. We also assessed the effect of walking speeds by comparing joint moments during the self-selected and fast speeds. To compare the stance phase of gait cycle we adapted the method utilized by Kuenze et al. [13] and McKeon et al. [16]. The group mean values of external moments for sagittal, frontal and transverse plane were calculated at each 1% of stance phase, and these values were plotted graphically with upper and lower limits of 95% confidence intervals (CI) for each comparison. Statistical significance was defined as




*(caption on next page)*

**Fig. 1.** Effect of gait speed on knee and hip moments in sagittal plane. Continuous lines indicate mean values and dotted lines indicate upper and lower limits of 95% confidence intervals.

portions of the gait cycle where 95% CIs did not overlap for a minimum of five consecutive percentages of the gait cycle stance phase.

## 3. Results

### 3.1. Sagittal plane

The were no differences between groups or legs (Supplementary material), however, there were differences between gait speeds for knee and hip moments. Knee flexor moments were universally higher during the early stance phase at the fast speed compared to the self-selected speed for the ACLR group reconstructed leg (0–7% of stance phase, Fig. 1A), ACLR group uninjured leg (4–9% of stance phase, Fig. 1C), control group preferred leg (0–6% of stance phase, Fig. 1E) and control group non-preferred leg (0–4% of stance phase, Fig. 1G). The knee extensor moment was also higher at the fast speed but at the end of the stance phase for the ACLR group uninjured leg and control group non-preferred leg at 95–100% and 96–100% of the stance phase, respectively. For the hip, there was higher extensor moment at the fast speed compared to the self-selected speed at the beginning of the stance phase (0–14% for the ACLR group reconstructed leg, 7–14% for the ACL group uninjured leg, 0–12% for the control group preferred leg, and 0–13% for the control group non-preferred leg, Fig. 1); Additionally, at the end of the stance phase there were higher extensor moments at fast speed compared to the self-selected speed but only for the ACLR group uninjured leg (89–95% of stance phase, Fig. 1D).

### 3.2. Frontal plane

There were differences between groups during fast speed; the ACLR group uninjured leg had lower ankle abductor moments than the control group preferred leg at the second half of the stance phase (65–99%, Fig. 2A). There were no differences between legs of the same group (Supplementary material). However, there were differences between speeds but only for the control group; the preferred leg demonstrated higher magnitude at the fast speed compared to the self-selected speed throughout the second half of the stance phase (58–98%, Fig. 2B).

### 3.3. Transverse plane

There were between group differences across all three lower extremity joints. The ACLR group reconstructed leg demonstrated lower ankle external rotator moment than the control group non-preferred leg (29–35% of stance phase) during fast speed (Fig. 3A). The ACLR group uninjured knee had higher knee external rotator moment than the preferred leg of the control group (46–64% of stance phase) at preferred speed (Fig. 3B) while both legs of the ACLR group had lower knee external rotator moment than the non-preferred leg of the control group (6–28% and 5–16% of stance phase, respectively, Fig. 3C-D). The ACLR group uninjured leg had higher hip external rotator moment than the control group preferred leg at both gait speeds, at midstance phase during self-selected gait speed (52–59%, Fig. 3E) and at the end of the stance phase during fast gait speed (94–100%, Fig. 3F).

Within group comparisons demonstrated no differences between legs for any joint in the ACLR group (supplementary material). However, the control group demonstrated difference between legs at the self-selected gait speed for ankle and hip at midstance phase (46–55% and 44–63%, respectively, Fig. 4A-C) and for the ankle only at the fast gait speed (at 30–45% of stance phase, Fig. 4B).

Gait speed demonstrated differences only in the control group with higher ankle and knee external rotator moments at fast speed for the non-preferred leg (23–36% and 23–30% of stance phase, respectively, Fig. 5). The preferred leg of the control group and both legs of ACLR group were not affected by gait speed change (supplementary material).

## 4. Discussion

The aims of study were to identify differences between groups (ACLR vs control group), legs within groups and gait speed for ankle, knee and hip joint moments in three planes throughout the stance phase of the gait cycle. There are three main findings: a) there were largely no differences between the reconstructed leg when compared to the uninjured leg or the control group indicating that at 4 years after surgery gait kinetics have largely normalized, b) there were consistently higher joint moments during fast speed walking compared to self-selected speed and c) the healthy leg of the ACLR group demonstrated higher knee and hip external rotation moments compared to the preferred leg of the control group which may be associated with higher injury risk.

Altered joint loading in sagittal plane longer than 4 years following ACLR is potentially associated with risk of early onset joint degeneration [9]. ACLR individuals tend to restore peak knee flexion angle 6 years after surgery [9]. For moments, very limited evidence indicates that lower peak knee flexor moment may be present in individuals 12 months or more post-ACLR while after 3 years there is no difference for

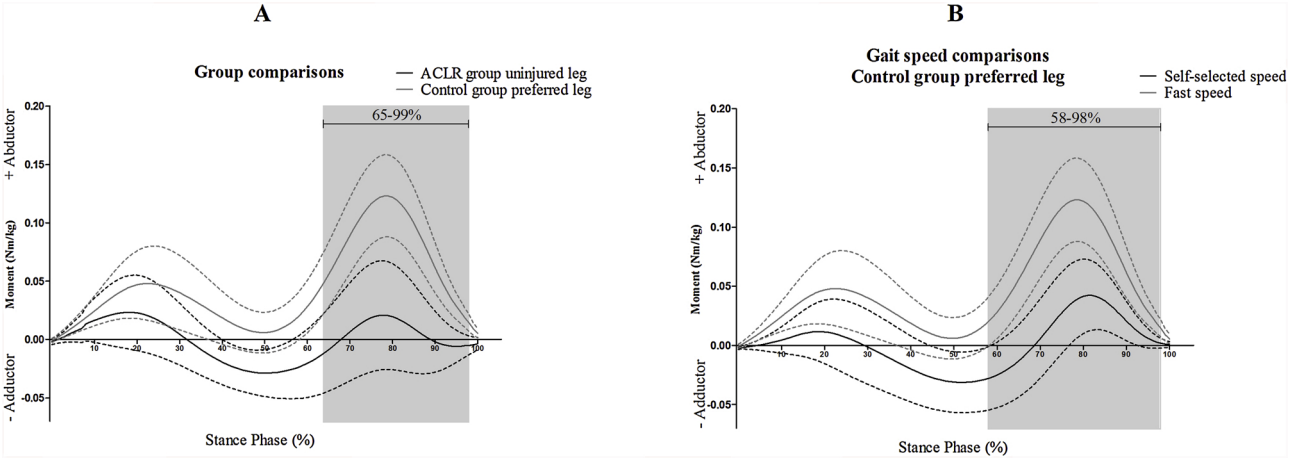



**Fig. 2.** Groups difference and effect of gait speed on ankle moments in frontal plane. Continuous lines indicate mean values and dotted lines indicate upper and lower limits of 95% confidence intervals.

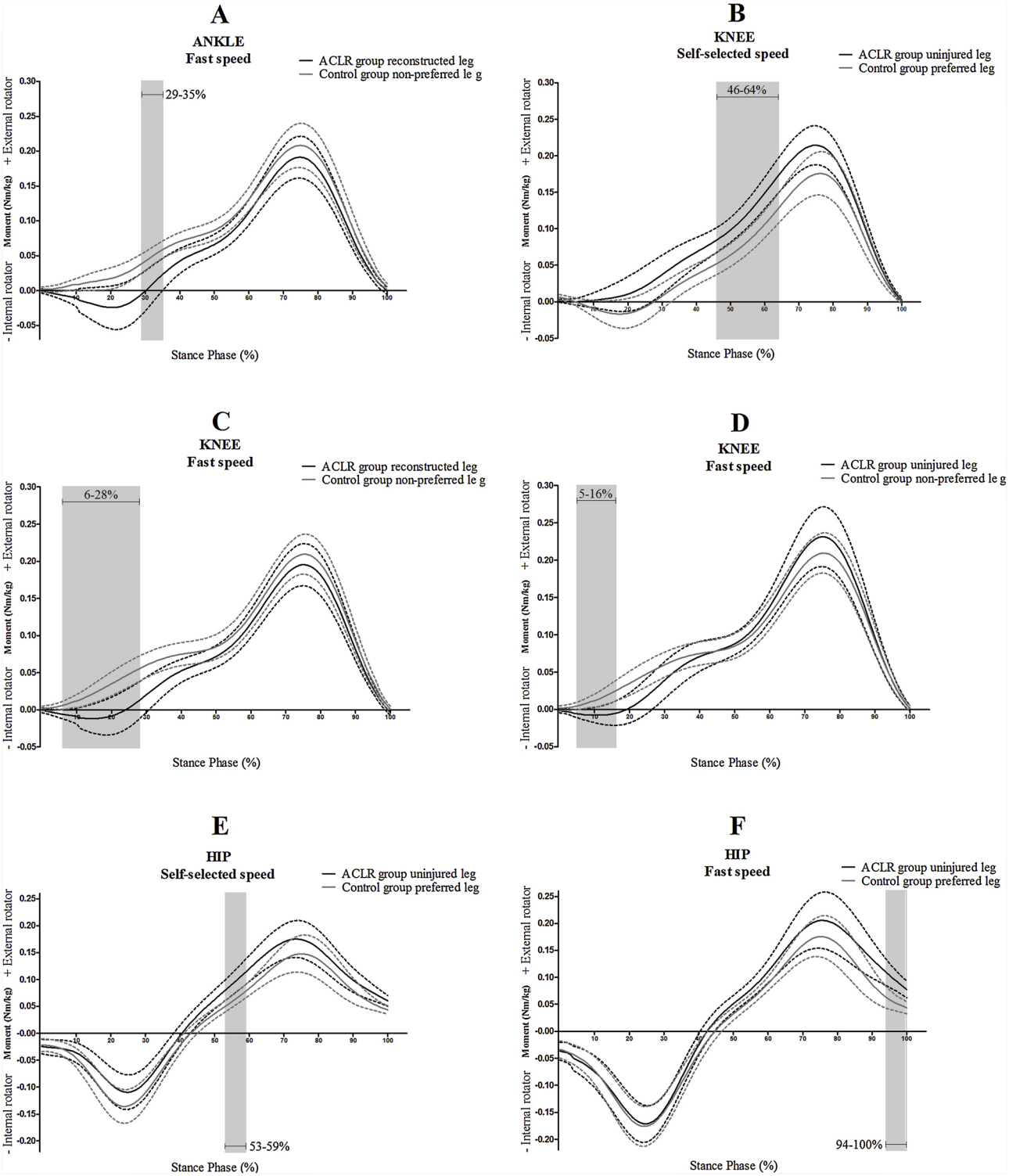



**Fig. 3.** Groups difference on ankle, knee and hip moments in transverse plane. Continuous lines indicate mean values and dotted lines indicate upper and lower limits of 95% confidence intervals.

extensor and flexor moment compared to contralateral the limb and healthy individuals [8]. Our findings add further support to this as we found no difference at long-term in sagittal plane moments between legs and groups, indicating that maybe joint kinetics tend to restore over time after surgery similar to kinematics. Contrary to our hypothesis, not only we found largely no higher joint moments in the reconstructed but also lower knee external rotation moment. One possible explanation for this is an offset of 1.3° to 3.0° of tibia external rotation after ACLR [17], that may cause a lower external rotator moment. Future research should investigate if the offset into external rotation after reconstruction correlates to lower knee external rotation moments.

On the other hand, when walking speed was increased we expected a general increase in joint load, particularly in the sagittal plane [11]. In this study, knee and hip extensor and flexor moments in increased with increasing speed, confirming partially our hypothesis. This effect

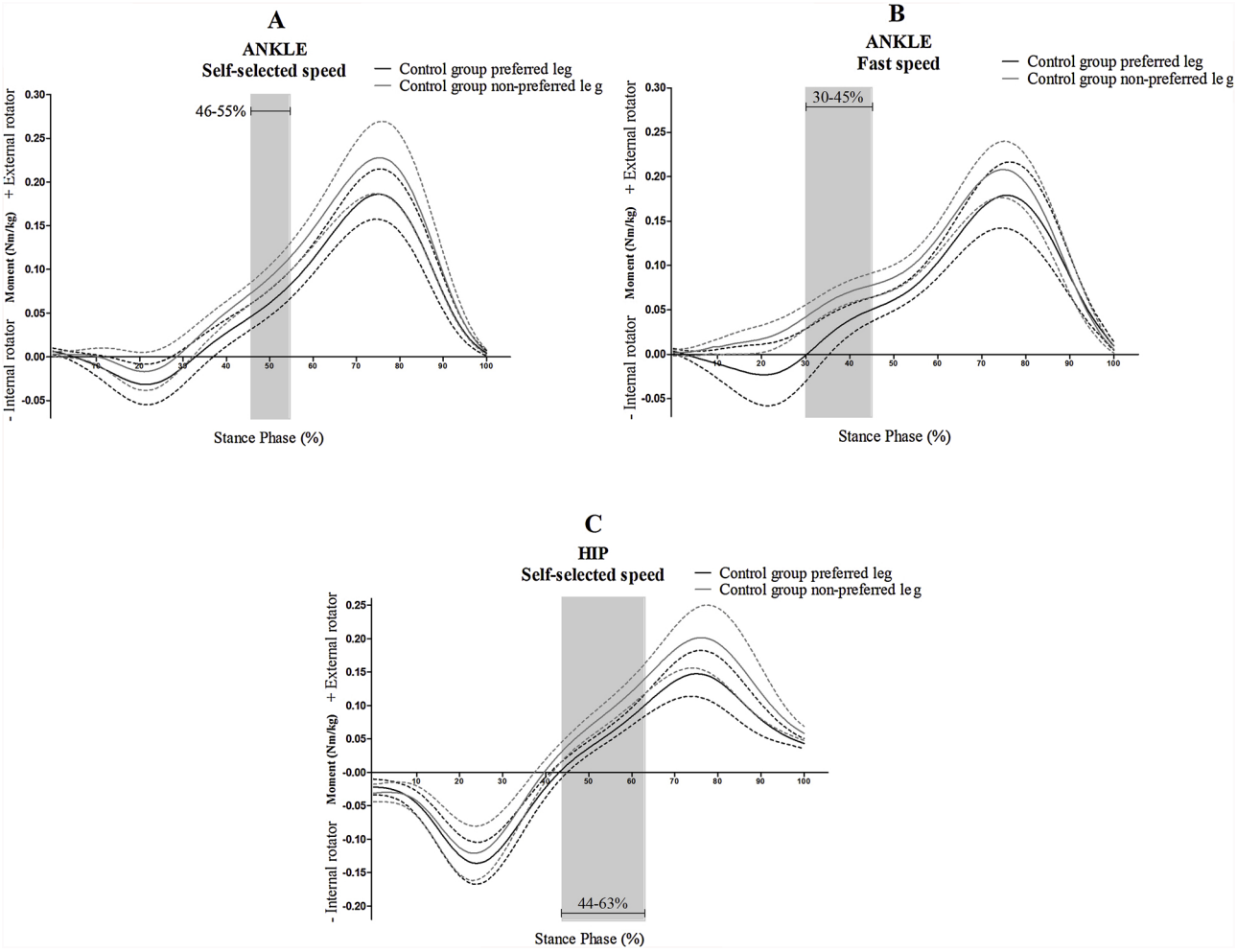



**Fig. 4.** Within group legs difference on ankle and hip moments in transverse plane. Continuous lines indicate mean values and dotted lines indicate upper and lower limits of 95% confidence intervals.

was observed at the beginning and the end of stance phase. Maybe it can be explained by the increase of ground reaction force peaks, which occur especially in these phases. Since the peak of flexor and extensor moments occurs at the beginning and the end of stance phase, respectively [18], this speed effect was not a surprise. Considering the use of faster walking speeds for incremental physical fitness programs [11], this needs attention by professionals working with populations at risk for degenerative joint development. High sagittal plane moments can lead to knee joint instability and can increase hamstring and quadriceps co-contraction and result in higher compressive loading on the articular cartilage, which may contribute to the progression of knee osteoarthritis (OA) [19].

The ACLR group uninjured leg had higher magnitude than the control group preferred leg for knee and hip external rotator moments. Considering that these differences were observed in the uninjured leg of the ACLR group that has a known predisposition to ACL injury [20] it raises the possibility that it may contribute to the mechanism of injury. External rotation of the knee, especially when combined with knee valgus may cause ACL tear via impingement with the lateral femoral condyle [21].

There are certain limitations in this study. Primarily, we did not control the surgical technique or rehabilitation protocols, we only confirmed that all participants received rehabilitation. Secondly, our results cannot be extrapolated to females, since there are differences between sex and we only assessed males. Finally, we need to be careful with interpreting the findings, particularly in the transverse plane that has larger measurement errors compared to the other planes.

## 5. Conclusion

In conclusion, lower extremity gait kinetics seem to be largely normalized 4 years after surgery. This study compared moments between a self-selected and a faster speed; larger moments were observed at faster speeds. Finally, the uninjured leg of the ACLR group demonstrates larger knee and hip external rotation moments compared to the preferred leg of the control group.

## Authors' contribution

KJVS participated in the design and conceived of the study, performed collection, processing and analysis of the data, and drafted the manuscript. EP participated in the design of the study and helped to draft the manuscript. CBM participated in the design and coordination of the study and helped to draft the manuscript. All authors read and approved the final manuscript.

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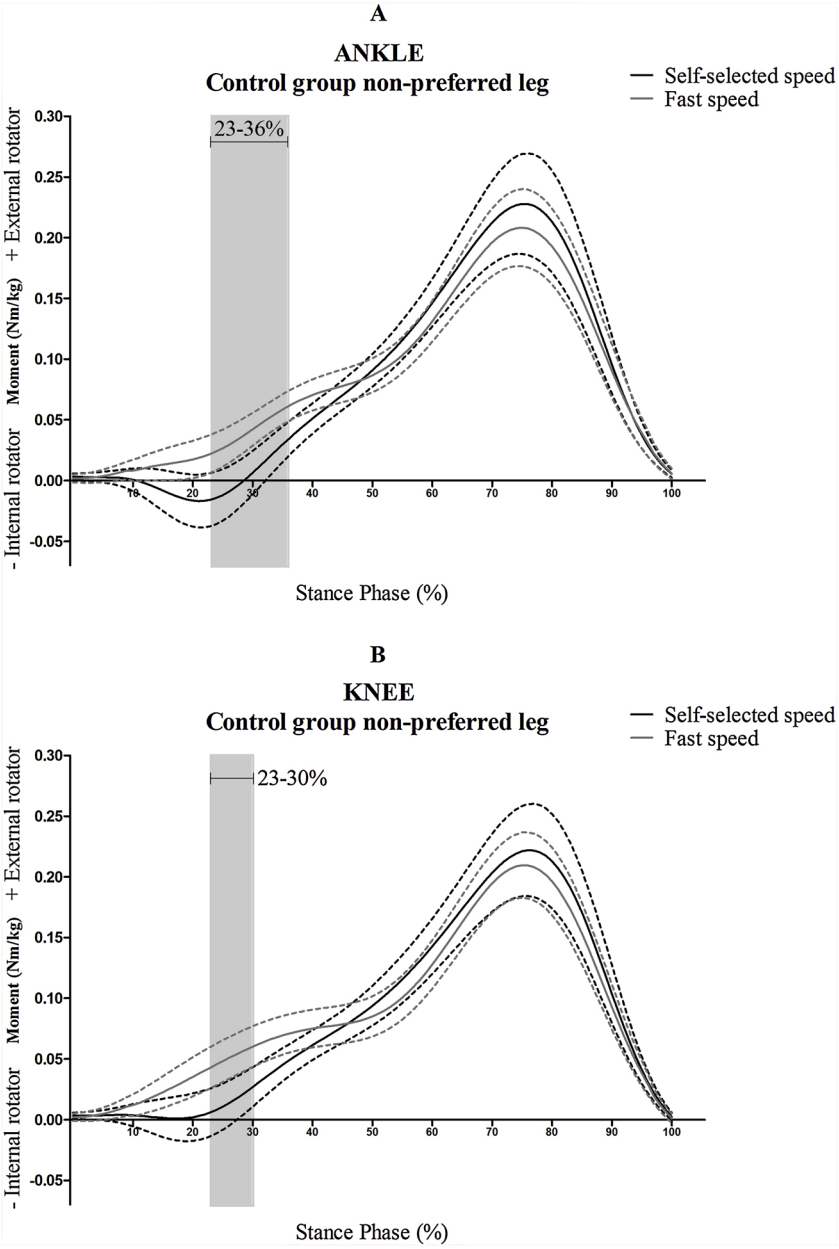


**Fig. 5.** Effect gait speed on ankle and knee moments in transverse plane. Continuous lines indicate mean values and dotted lines indicate upper and lower limits of 95% confidence intervals.

## Conflict of interest statement

There is no conflict of interest for any of the authors.
Declarations of interest: none.

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