NEUROMUSCULAR FUNCTION DURING MAXIMUM INTENSITY SIDESTEP-CUTTING MANOEUVRE: EXPLORING THE INFLUENCE OF ANTICIPATION AND PRIOR ACL INJURY

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This study focuses on understanding the consequences of Anterior Cruciate Ligament (ACL) injuries and their rehabilitation effectiveness by comparing muscle forces in planned and unplanned movements between healthy and reconstructed ACL limbs. 3D motion and ground reaction force data were collected from high-performance athletes who underwent reconstructive surgery and performed a sidestep cut. Results showed lower limbs with a reconstructed ACL had lower contributions of the *vasti* to anterior accelerations. Furthermore, athletes performing unanticipated manoeuvres had a greater *gastrocnemii* contribution to posterior accelerations, indicating a higher mechanical ACL load. These findings highlight the importance of optimizing ACL rehabilitation, as muscle function may not be fully restored, potentially contributing to the recurrence of ACL injuries.

KEYWORDS: Sidestep Cut, ACL Injury, Musculoskeletal Modelling, Induced Acceleration Analysis.

INTRODUCTION: Change of direction represents a predominant mechanism of an ACL injury, accounting for up to 50% of cases (Alentorn-Geli et al., 2009). From this, the need for reconstructive surgery (ACLR) usually arises, which itself translates into a possibility of injury reoccurrence associated with the loading asymmetry between the reconstructed and healthy ligament. Previous research revealed discernible kinematic and kinetic distinctions between limbs during both anticipated and unanticipated change of direction tests nine months post-surgery, notwithstanding the absence of statistically significant disparities in performance time (King et al., 2020). Moreover, biomechanical distinctions between tests were identified in variables previously linked to the mechanism of ACL injury during unanticipated change of direction manoeuvres. However, to our knowledge, no study has yet examined differences in neuromuscular function between limbs during both anticipated and unanticipated change of direction tasks as athletes return after ACLR. Understanding the biomechanical roles of individual muscles and the way they contribute to not only centre of mass (COM) but also joint and segment accelerations, can help design training programs to rehabilitate from an injury and prevent injury recurrence. However, the phenomenon of dynamic coupling (i.e. Multi-joint movements require a harmonious collaboration between the muscles to achieve the desired movement), makes the use of musculoskeletal simulations able to obtain such muscle contributions necessary. The main purpose of this work was to compare the contributions of muscle forces to COM acceleration and A/P tibial acceleration between lower limbs with a healthy and reconstructed ACL during different sidestep-cutting manoeuvres performed by elite field sports athletes, making it possible to study and characterise the consequences of the ACL injury. Anticipated and unanticipated tasks will be studied so that it is possible to characterise the effect of unpredictability on the mechanical load, which is relevant and more representative of a real game situation.

METHODS: A total of 34 eligible participants were recruited between January 2019 and November 2019. For data collection only male athletes between 18 and 35 years old that participate in a field-based sport involving cutting/change of direction (Gaelic Football, Hurling, Soccer, Basketball, etc) who had had a primary ACL injury and had the intention to return to the same level of physical activity following rehabilitation. Participants were part of a long-term research project consisting of physical testing at 6- and 9-months post ACL Reconstruction (ACLR) and were recruited from the caseload of two orthopaedic surgeons in the Sports Surgery Clinic in Dublin. All subjects suffered an ACL injury and an ACLR was completed using either a patellar or a quadriceps tendon graft technique. Only a subset of five participants (mass: 82.3 ± 17.4 kg; height: 178.2 ± 8.7 cm; time post-op: 39.8 ± 3.9 weeks) of an undisclosed field team sport was studied for this work. All subjects performed several planned and unplanned sidestep cuts for both directions, and the best trial for each variation was selected and analysed. The experimental protocol is fully described in (King et al., 2020). Biomechanical data were collected using a ten-camera motion analysis system (200 Hz; Bonita-B10, Vicon, UK), synchronized with two force platforms (1000 Hz BP400600, AMTI, USA) recording the positions of 42 reflective markers. The employed marker set was a combination between the Plug-in Gait model and the 6 Degrees of Freedom model, and a full description of the marker set is given in (Scott, Robinson, & Daniels, 2020). The musculoskeletal modelling was implemented in OpenSim (version 4.3) (Delp et al., 2007). For this work, the implemented musculoskeletal model used was the gait2392 model. This model comprises 23 degrees of freedom and 92 muscle-tendon actuators representing 76 muscles of the lower limbs and the torso. This generic model was scaled using the OpenSim scaling tool to have a more accurate representation of the athlete in study. Then, inverse dynamics (ID), residual reduction algorithm (RRA), and computed muscle control algorithm (CMC) are executed to compute muscle forces. With the outputs of the previously mentioned CMC tool, it is possible to run the induced accelerations analysis (IAA) tool to calculate each muscle's contribution to total COM and A/P tibial acceleration. The time interval that is being studied corresponds to the ipsilateral foot's contact with the ground following the athlete's approach to the force platforms. Two Wilcoxon tests assessed the significance of comparisons between ACLR and healthy lower limbs, as well as between planned and unplanned sidestep-cutting manoeuvres. To adjust for multiple comparisons, a significance level of 0.025 was employed, following the Bonferroni Correction, ensuring a 97.5% confidence interval.

RESULTS: The figure below shows the average muscle contributions to vertical, anteroposterior, mediolateral COM accelerations, and anteroposterior tibial acceleration, during ipsilateral foot contact, for each lower limb and both the anticipated and unanticipated version of the manoeuvre.

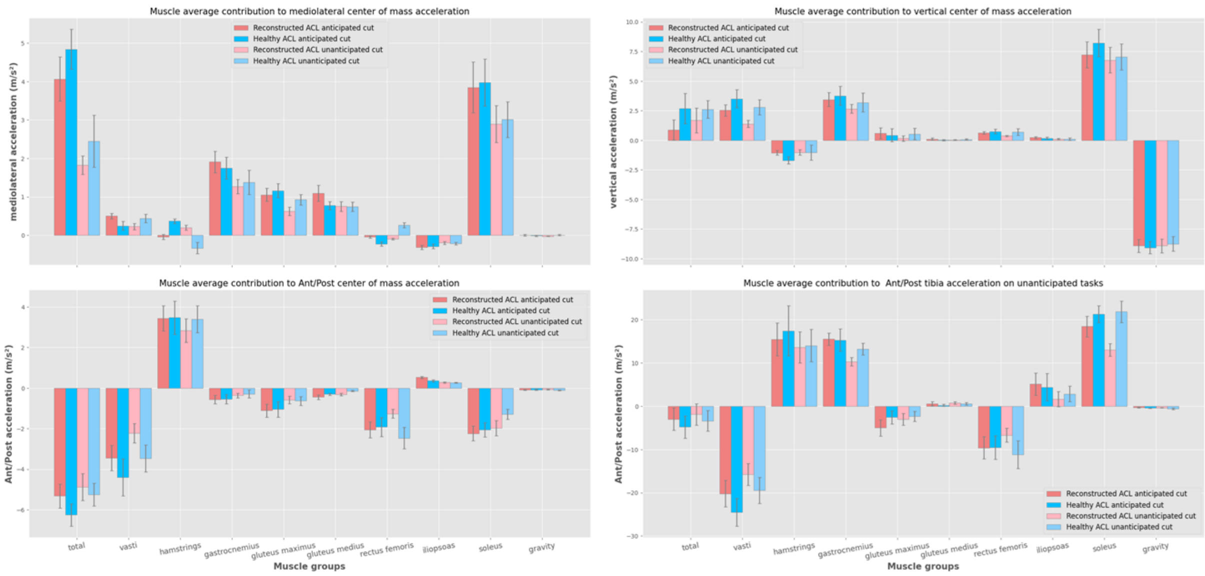

Figure 1. Average values of muscle contribution for COM and tibial A/P acceleration curves for all 4 task variations. Total accelerations and gravity contributions are also represented. Error bars are ±1 standard error. Positive values refer to the cutting direction along the mediolateral direction. Along the A/P direction, positive values refer to the anterior direction. Along the vertical direction, values refer to the upwards direction.

DISCUSSION: The objective of this work was to compare the contributions of muscle forces to COM acceleration and A/P tibial acceleration between lower limbs with a healthy and reconstructed ACL during different sidestep-cutting manoeuvres performed by elite field sports

athletes. Significant findings from Wilcoxon test include higher greater *vasti* contribution to posterior acceleration (p = 0.01953) in the healthy ACL limb versus the reconstructed limb. These findings suggest the presence of loading imbalances, indicating that the reconstructed ACL experiences heightened mechanical stress. Additionally, the *gastrocnemii* showed greater contribution to posterior COM acceleration during anticipated manoeuvres compared to unanticipated ones (p = 0.00585), implying reduced mechanical strain on the ACL.
Concerning vertical acceleration, the principal contributors include the *vasti*, *gastrocnemii*, and *soleus*, aligning with existing literature, both strictly model based (Mateus et al, 2022), and model based with additional comparison between predicted activation and experimental electromyography recordings (Maniar et al, 2019). The *gluteus maximus* assumes a noteworthy role in initial vertical acceleration, diminishing as the task progresses (Maniar et al., 2019). Remarkably, hamstrings exhibit a counterproductive effect on vertical COM acceleration, consistent with Mateus et al.'s findings (2022). This phenomenon can be attributed to the antagonistic relationship between hamstrings and quadriceps. While evident in anteroposterior and mediolateral contributions, further investigation is warranted.
Mediolateral redirection denotes the acceleration of the COM toward the designated cutting direction. This study identifies key contributors to this acceleration, including the *gluteus maximus* and *medius*, *gastrocnemii*, and *soleus* muscles. While prior literature, e.g., (Maniar et al., 2019) and (Mateus et al., 2022), highlights the *vasti* muscles as primary mediolateral contributors, our findings reveal their negligible impact compared to the significant contributions of muscles like the *soleus*. Although this may be related to differences in the models used for these simulations and the tasks studied, further investigation is warranted. The employed musculoskeletal model, based on a one-degree-of-freedom planar knee joint (Yamaguchi & Zajac, 1989), lacks *varus* and *valgus* degrees of freedom, potentially accounting for discrepancies with previous contributions reported. However, since parallels between kinematic constraint reaction forces and experimental ground reaction forces can be drawn and the fact that all simulations were performed according to Hicks *et al* (2015) gives confidence to our results.
The principal contributors to posterior COM acceleration predominantly stem from the quadriceps, with the hamstrings posited as potential counterforces, hindering anterior tibial translation. These findings align with prior research (Maniar et al., 2019; Mateus et al., 2022). Wilcoxon tests reveal a significantly heightened posterior contribution of the *vasti* muscles in the lower limb with intact ligaments compared to those post ACLR. Results also show the *vasti* as the main contributors to posterior tibial acceleration which counteracts anterior shear force and, therefore, is responsible for unloading the ACL (Maniar et al, 2018). Thus, given the lower *vasti* muscle force in the ACL compared with the healthy limb, it is concluded that the reconstructed ligament is subject to higher mechanical loading. Notably, gastrocnemii exerted a greater impact on posterior COM accelerations during planned versus unplanned sidestep cuts, aligning with the insights of Besier *et al.* (2001) on movement planning's pivotal role in knee moments and ligament injury risk. *Gastrocnemii*'s unexpected posterior contribution may indicate a stabilizing role during stopping (Xie et al, 2013), aiding ankle joint control or supporting other muscles for directional force generation. While no validation was conducted, this deviation from the expected anterior contribution underscores potential multifaceted roles of *gastrocnemii* during sidestep cutting manoeuvres. The observed posterior contribution of *gastrocnemii* aligns with Mokhtarzadeh et al. (2013), suggesting an antagonistic role against ACL loading. Anticipated cutting exhibits a statistically significant higher posterior contribution, potentially reducing ACL mechanical load compared to unanticipated cutting, in line with Besier et al. (2001), who highlight the heightened risk of non-contact knee ligament injuries without adequate anticipation and planning.

CONCLUSION: The estimation of muscle contributions to COM and tibial accelerations allowed to better compare the athletes' lower limb recovering from an ACL reconstruction, and the healthy lower limb. As well as to reach the conclusion that this difference becomes statistically significant when analysing the *vasti* muscle group force and posterior contribution to the COM acceleration, which were higher for the healthy lower limb. With these results, it is possible to identify loading asymmetries as the reconstructed ACL is subject to a greater mechanical load. In conclusion, using musculoskeletal modelling it was possible to estimate the mechanical load during the sidestep cutting manoeuvre and to understand the consequences of an ACLR and the impact of the anticipation factor.

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