ANKLE PLANTARFLEXOR CONTRIBUTIONS TO KNEE JOINT LOADING AND ANTERIOR CRUCIATE LIAGAMENT FORCE DURING SINGLE-LEG LANDING

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The purpose of this study was to identify the effects of height on ankle plantarflexor contributions to the knee joint loading and the anterior cruciate ligament (ACL) force during single leg landing. Eight healthy subjects performed landing from 30 and 60 cm heights. Subject-specific musculoskeletal models, based on single-leg landing, were developed in OpenSim using kinematics and kinetics data. Predicted muscle forces and knee joint reaction forces were input into another knee model to estimate ACL forces during landing. Large Soleus muscle forces (~5B.W.) were found to act on the tibia at the same time when peak ACL forces occurred. The Gastrocnemius muscles, which acted as an ACL antagonist peaked earlier than the Soleus with a lower magnitude (~3BW). The Gastrocnemius-Soleus complex acted to stabilize the knee joint during single leg landing.

KEY WORDS: acl injury, gastroc-soleus complex, single-leg landing.

INTRODUCTION: Single-leg landing is an athletic manoeuvre that involves high knee injury risk that can lead to anterior cruciate ligament (ACL) injury. About 70% of ACL injuries are non-contact and sustained when landing from a jump, cutting, or sudden deceleration. Muscle recruitment and knee stability during single leg landing from different heights is therefore of significant interest in order to help prevent ACL injury. Muscles such as Hamstrings (Hams) and Quadriceps (Quads) responsible for knee stability have been well studied, but few studies investigated the Gastrocnemius (Gas) and Soleus (Sol) muscles effect on the knee joint loading. The main function of the Gas- Sol complex is to stabilise the ankle joint. However, various investigators have speculated that the Gas-Sol complex could contribute to knee stability, preventing ACL injury (Boden, Torg, Knowles, & Hewett ,2009; Podraza, & White, 2010). In this study, we therefore aim to find the Gas-Sol muscles forces during single leg landing to further understand how these muscles' coordination patterns changes with increased height and subsequently ACL forces. We hypothesized that at the instance of peak ground reaction force (GRF) where injury is most susceptible i.) the Gas and Sol muscle forces and ii.) the ACL force would increase with an increase in landing height.

METHODS: Eight healthy male subjects were recruited (22.9 ±0.6 y, 1.70 ±0.03 m, 67.2 ±6.9 kg). Informed consent was obtained from the participants, in compliance with the institutional ethics review board. The subjects performed single leg landing from heights of 30 and 60 cm which has been studied extensively in previous studies. The subjects' kinematics and kinetics data were collected using a 6 cameras motion analysis system (Vicon MX, Oxford Metrics, UK) and two force plates (Kistler, Winterthur, Switzerland) recording ground reaction forces (GRF). Standard inverse kinematics and Residual Reduction Algorithm (RRA) were employed to produce a set of dynamically consistent joint angles (Figure 1). Following, static optimization method was utilized to predict muscle forces. The Opensim software was used to create subject specific musculoskeletal models including 92 muscle tendon units of the lower limb (Delp, Anderson, Arnold, Loan, Habib, John, Guendelman, & Thelen, 2007). Joint reaction analysis in the model was used to calculate forces at the knee joint. Using these forces, a separate 2-D knee model was used to calculate the ACL forces during the single leg landing (Kernozek, & Ragan, 2008; Laughlin, Weinhandl, Kernozek, Cobb, Keenan, &

O'Connor, 2011). Landing phase was defined from foot strike (0%) to maximum knee joint flexion angle (100%). A paired t-test was used to identify differences in variables between the landing manoeuvres at peak GRF.

RESULTS: The Gas and Sol muscle forces were compared with Hams muscle force during landing and at peak GRF from different heights. This is because Hams muscle is believed to protect ACL injury by preventing anterior tibial translation. The muscles forces were also analysed at the instance of peak GRF as it is anticipated to be the most susceptible instant of ACL injury. ACL forces were compared at different heights. The GRF for the eight subjects increased with increased landing heights (p=0.004). Peak GRFs occurred during early phases of the landing, between 10 to 50%. Increased height also resulted in greater knee joint forces (Table 1). Larger Quads and Hams forces were also observed at 60 cm when compared to 30 cm landing heights.

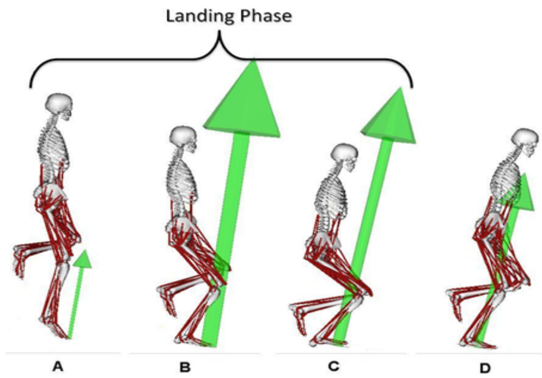

Figure 13: Single leg drop landing maneuver. A: Foot strike, B: Peak GRF, C: Peak knee flexion angle, D: Prepare for subsequent step.

At the instance of peak GRF, the Quads muscles could reach 5 times Body Weight (BW) and 3 BW for 60cm and 30 cm landing heights, respectively. Similarly, the Hams recorded 4BW and 2 BW, respectively for the two landing heights (Table 1). The Gas and Sol peaked at different times from that of the Quads and Hams within the landing phase. Gas force reached its peak in less than 20% of the landing phase. Also, an average 168% increase was observed in peak Gas force when subjects landed from 60 cm compared to 30 cm at peak GRF(p=0.040) . Comparison of Gas with Hams muscle forces showed that Gas muscle registered lower magnitude (Figure 2A) and peaked at the very early phase of landing manoeuvres. Contrary to Gas muscle forces pattern, peak Sol muscle forces did not happen in early landing phase. Very large forces were exhibited by Sol muscle during mid landing phase. At peak GRF, Sol force was about 8BW for 60 cm whereas at 30 cm landing, Sol forces could reach 4 BW (p=0.019).

Table 7: Sol , Gas Quads, Hams muscles forces and Knee joint reaction and ACL forces during single leg landing from 30 and 60 cm at peak GRF. Forces normalized by B.W.

Forces at peak GRF	30cm	60cm	p-value
GRF	3.24±.63	4.38±0.87	0.004
Hamstrings muscle	2.36±2.03	3.75±1.56	0.024
Quadriceps muscle	3.53±1.50	5.16±2.28	0.050
Soleus muscle	4.11±0.82	7.90±3.62	0.019
Gastrocnemius muscle	0.59±0.23	1.58±1.11	0.040
Knee Joint Reaction	9.64±3.66	14.83±4.81	0.005
ACL	0.52±0.35	0.65±0.55	0.156

Although Sol forces were much higher throughout landing, peak Hams occurred earlier in the first phase of landing for both landing heights. Knee joint reaction forces demonstrated ~53% increase at 60 cm compared to 30 cm height landing. The knee joint reaction forces then dramatically elevated to about 14 BW and 9 BW for 60 and 30 cm at peak GRF respectively (p=0.005). Similar to GRF and Gas forces peak timing, knee joint reaction forces peaks happened in early phases of landing. Finally, ACL force peak occurred right following the foot strike. At peak GRF, ACL force reached 0.65B.W for 60 cm whereas this was 0.52B.W for 30 cm landing task (p=0.156) (Table 1). However, comparison of ACL peaks during landing showed that landing from greater height increased peak ACL forces (p=0.03).

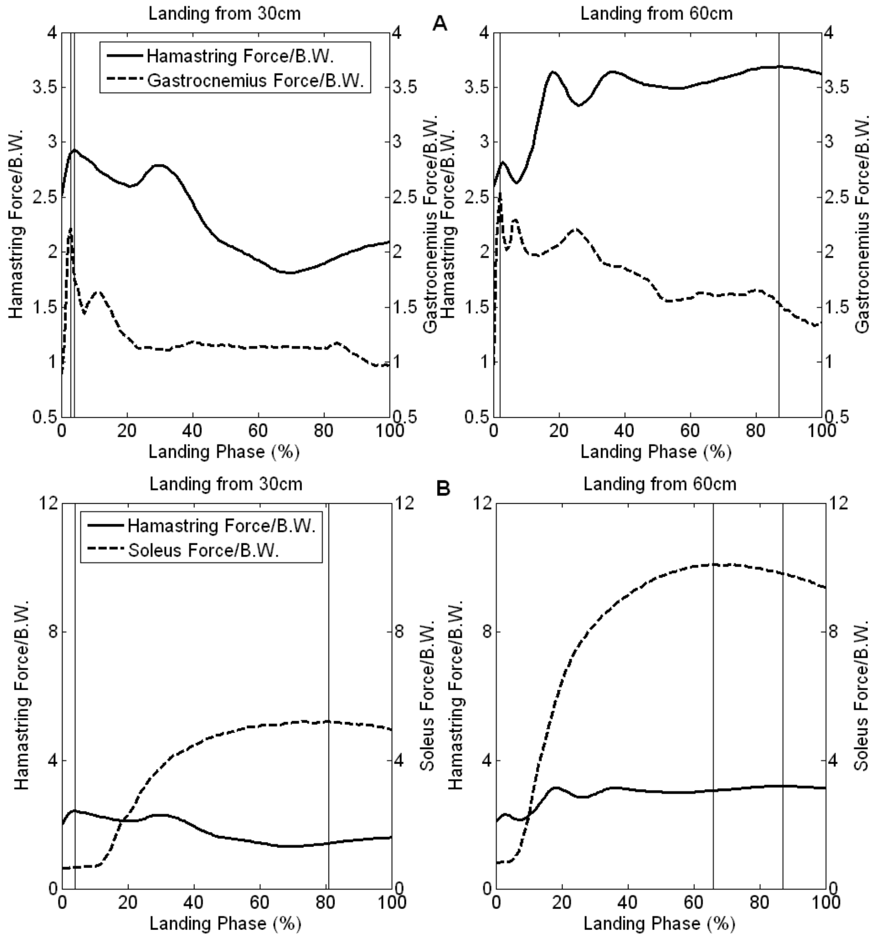

Figure 14: Gas and Hams muscle forces during landing (A), Sol and Hams muscle forces during landing (B) during single leg landing from 30 and 60 cm. Vertical lines show maximum values.

DISCUSSION: Subject specific musculoskeletal models of single leg landing tasks were developed. The aim of this paper was to study the effect of landing height on ankle plantarflexor contributions, knee joint loading and ACL forces during single-leg landing. Our findings showed that at peak GRF, Gas and Sol muscle forces increased with an increase in landing height. However, ACL force did not increase significantly during landing at peak GRF when landing from 60 cm (p=0.156). This result disproved our second hypothesis. Because of a lack of increase in ACL force, the increase in Gas and Sol muscle forces may be interpreted as stabilizing both the ankle and knee joint when comparing landing from 60 cm to that of 30cm.

It is likely that if there is any muscle impairment present in either the Gas or Sol muscles during landing, the ankle joint kinematics will be affected and the muscles surrounding the knee joint may not be able to compensate the extra loading due to the unstable ankle, leading to possible ACL injury. Also, major muscles spanning ankle joint are being compared with Hams muscles to better understand their possible synergic effect during landing. Ham muscle seem to be protective of knee joint during landing (Withrow, Huston, Wojtys, &

Ashton-Miller, 2008), because its posterior force may unload the ACL. Anterior tibial translation (ATT) is known to create high forces on the ACL. Thus the muscles such as the Hams, Gas and Sol which may act to influnence ATT are of siginificant interests. For instance, Gas seems to act parallel to tibia because of its line of action; therefore, it may not affect Anterior/Posterior motion of the tibia with respect to femur. However, Gas is responsible for ankle plantarflexion. Similarly, the role of the Sol muscle is to prevent dorsiflexion and stabilize the ankle joint. This muscle may not have direct effect on the knee joint loading because of its line of action that does not span the knee joint.
Furthermore, Gas and Sol muscles seem to stabilize predominantly the ankle joint. However, the results of this study compared with previous in vitro experiments could suggest that large forces exerted by calf muscles may play important role in knee loadings. In vitro experiments revealed that Sol muscle could act as ACL agonist while Gas muscle acted as an antagonist. (Elias, Faust, Chu, Chao, & Cosgarea, 2003). In the present study, lower forces of Gas following foot strike were seen while much greater Sol forces were present after peak Gas. There was 92% increase in Sol muscle force at peak GRF while this was less than 60% for Hams muscle forces at 60cm compared to 30 cm (3.8 vs. 1.39 BW respectively). These changes were small for Gas muscle forces (~1 BW.). This very large Sol muscle force in early stages of landing phase could not only decrease ankle dorsiflexion but also act as a posterior tibia force to potentially protect ACL. Therefore, large Sol muscle forces during safe single leg landing could be an indicator of both ankle and knee joint stability. The reason that the peak Sol forces happened almost at the end of the landing could be due to fact that high forces is needed to stabilize the knee joint at maximum knee flexion. More detail modelling of the influence of Sol and Gas muscle forces on ligaments forces as well as knee joint reaction forces are required to shed light on the effect of each muscle on ACL force during landing.
Apart from motion analysis accuracy, another limitation of our study was the use of a 2D knee model to estimate ACL force, which may not be completely representative of the dynamic model of the impact type landing manoeuvres. Other higher resolution models such as Finite Element models that can include ligaments, knee joint geometry, cartilage and bone could provide more detail information.

CONCLUSION: The muscle forces surrounding the ankle joints may indirectly help to protect the knee joint and ligaments such as the ACL. The Gas and -Sol muscles complex could be taken into account in future training methods in order to provide stability to the knee joint.

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