ARTICLE IN PRESS

Journal of Biomechanics ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at SciVerse ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Contributions of the Soleus and Gastrocnemius muscles to the anterior cruciate ligament loading during single-leg landing

Hossein Mokhtarzadeh [a], Chen Hua Yeow [b,c], James Cho Hong Goh [b], Denny Oetomo [a], Fatemeh Malekipour [a], Peter Vee-Sin Lee [a,*]

[a] Department of Mechanical Engineering, Melbourne School of Engineering, University of Melbourne, Victoria 3010, Australia
[b] Division of Bioengineering, Faculty of Engineering, National University of Singapore, Singapore
[c] School of Engineering and Applied Sciences, Harvard University, USA

ARTICLE INFO

Article history:
Accepted 14 April 2013

Keywords:
Soleus
Gastrocnemius
ACL injury
Single leg landing
Lower extremity

ABSTRACT

The aim of this study was to identify the contribution of the Soleus and Gastrocnemius (Gastroc) muscles' forces to anterior cruciate ligament (ACL) loading during single-leg landing. Although Quadriceps (Quads) and Hamstrings (Hams) muscles were recognized as the main contributors to the ACL loading, less is known regarding the role of ankle joint plantarflexors during landing. Eight healthy subjects performed single-landing tasks from 30 and 60 cm heights. Scaled generic musculoskeletal models were developed in OpenSim to calculate lower limb muscle forces. The model consisted of 10 segments with 23 degrees of freedom and 92 lower body muscle-tendon units. Knee joint reaction forces were calculated based on the estimated muscle forces and used to predict ACL forces. We hypothesized that Soleus and Gastrocs muscle forces have opposite effects on tibial loading in the anterior/posterior directions. In situations where greater landing height would lead to an increase in GRF and risk of ACL injury, we further hypothesized that posterior forces of the Soleus and Hams would increase correspondingly to help protect the ACL during a safe landing maneuver. Our results demonstrated the antagonistic and agonistic roles of Gastrocs and Soleus respectively in ACL loading. The posterior force of Soleus reached 28–32% of Ham's posterior force for both landing heights at peak GRF while the posterior force of Gastrocs on femur was negligible. ACL injury risk during single-leg landing is not only dependent on knee musculature but also influenced by muscles that do not span the knee joint, such as the Soleus. In conclusion, the role of the ankle plantarflexors should be considered when developing training strategies for ACL injury prevention.

1. Introduction

Single-leg landing is an athletic maneuver with one of the highest risks of anterior cruciate ligament (ACL) injury (Pappas et al., 2007; Yeow et al., 2011). Approximately 70% of ACL injuries are non-contact, and are sustained due to side cutting maneuvers or when landing from a jump (Griffin et al., 2000). To help prevent such injuries, the knee joint must be stabilized and protected from excessive loads on the joint's soft tissue and ligaments. Two key factors in the stabilization of the joint are lower limb muscle strength and muscle recruitment patterns.

In single-leg drop landing, anterior tibial translation (ATT) in the sagittal plane is primarily restrained by the ACL, particularly when muscles are not able to help stabilize the knee. Muscles that span the knee joint, such as the Hamstrings (Hams) and Quadriceps (Quads) play a crucial role in affecting ATT and ACL strain. Numerous studies have shown that the Quads act to increase ATT and hence ACL strain (i.e., they are an ACL antagonist), while the Hams are considered an ACL agonist, restraining ATT and reducing ACL strain (Hewett et al., 2007; Li et al., 1999; Myer et al., 2005; Pflum et al., 2004; Podraza and White, 2010; Renström et al., 1986). However, some investigators have speculated that muscles that stabilize the ankle joint, such as Gastrocnemius (Gastrocs) and Soleus could also contribute to knee stability and prevent ACL injuries. Fleming et al. (2001) reported Gastrocs to be an ACL antagonist using transcutaneous electrical muscle stimulation to induce Gastrocs, Quads and Hams in a controlled static study. Elias et al. (2003) used a knee simulator and cables to pull the muscle tendons in a cadaveric limb, and concluded Soleus to be an agonist and Gastrocs an antagonist to the ACL. And Sherbondy et al. (2003) used an arthrometer as well as cadaveric specimens, and found that both Soleus and Gastrocs were able to decrease ATT in ACL intact and deficient knees, simulating the effect of passive ankle dorsiflexion. However, these

* Corresponding author. Tel.: +61 38 34 44426; fax: +61 38 344 4290.
E-mail address: pvlee@unimelb.edu.au (P.V.S. Lee).

0021-9290/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jbiomech.2013.04.010

studies did not consider the dynamic loadings of a high risk motion, such as single-leg landing, and the experiments were not conducted under weight bearing and physiological loading conditions.

Motion analysis studies associated with biomechanical models could potentially predict muscle forces in high risk movements, such as single-leg landing. For instance, Pflum et al. (2004), Kernozek and Ragan (2008) and Laughlin et al. (2011) studied landing maneuvers and found that the tibiofemoral (TF) force, muscle forces of the Quads and Hams, and the ground reaction force (GRF) were the major contributors to ACL loading. Gastrocs was considered in their models, but was found not to have a major role in increasing ACL force; however, Soleus muscle forces were not included in these studies as Soleus does not span the knee joint. The role of Soleus in tibial loading is evident from a free body diagram (FBD) of the tibia (Fig. 1). Additionally, Soleus and Gastrocs muscles contribute to the magnitude and direction of the GRF, which plays a key role in ACL loading (Hashemi et al., 2011; Lin et al., 2011). Considering the muscle attachment sites of Gastrocs and Soleus on the tibia and the femur, the effects of Soleus and Gastrocs through the knee and ankle joints could potentially contribute to ACL loading. However, the magnitude of their association is not well understood.

The aim of this study was to predict the muscle forces acting posteriorly on the tibia and femur generated by the Soleus and Gastrocs muscles during single leg landing, and to understand how the muscle coordination patterns change with increased height and subsequently affect ACL loading. Our first hypothesis was that Soleus and Gastrocs muscle forces have opposite effects on tibial loading in the anterior/posterior direction. Soleus would help to protect the ACL during landing, but to a lesser extent than Hams. Greater landing height would lead to an increased GRF and risk of ACL injury. We also hypothesized that posterior forces of the Soleus and Hams would increase correspondingly to help protect the ACL during a safe landing maneuver.

2. Methods

2.1. Participants and motion analysis

Eight healthy male participants were recruited with a mean [standard deviation] age of 22.9 [0.6] years, height of 1.70 [0.03] m and weight of 67.2 [6.9] kg. This data was extracted from a larger study on different types of landing (Yeow et al., 2009a,b, 2010, 2011). The risk of ACL injury landing with left or right leg dominance is still an area of research (Ruedl et al., 2012; Sadeghi et al., 2000; Urabe and Iwamoto, 2009). To maintain the consistency among the participants, we selected only participants who are right-leg dominant in this study. Informed consent was obtained from the participants in compliance with the institutional ethics review board. The participants performed single-leg landing tasks from heights of 30 and 60 cm, to facilitate comparison with previous studies. Participants landed barefoot and with their dominant leg (identified as the preferred leg for kicking a ball; right leg for all participants).

Kinematic and kinetic data were collected using a 6-camera motion analysis system (Vicon MX, Oxford Metrics, UK) at a sampling rate of 400 Hz and a force plate (Kistler, Winterthur, Switzerland) recording ground reaction forces at a sampling rate of 1000 Hz. Retro-reflective markers (25 mm diameter) were attached to the lower body at 15 locations according to the Vicon Plug-in-Gait marker set. The upper body kinematic data were not collected. The following anthropometric measurements were acquired from all participants: height, weight, knee width, ankle width, leg length, and inter-anterior superior iliac spine distance. Vicon-Nexus software (Oxford Metrics, UK) was used for pre-processing of the kinematic and kinetic data.

The EMG data were collected with the Noraxon TeleMyo system (Noraxon USA, Inc., Scottsdale, AZ) at a sampling rate of 1000 Hz, whereby disposable surface electrodes were placed on the Quads, Hams, and Gastrocs. Similar EMG reduction method was used as conducted by Laughlin et al. (2011). The EMG data was processed using a high-pass filtered of 4th order, zero-lag, and recursive Butterworth filter with a cut-off frequency of 20 Hz, then full wave rectified and low-pass filtered with cut-off frequency of 15 Hz. Finally, peak EMG magnitudes were used to normalize the smoothed EMG data.

2.2. Scaled-generic musculoskeletal models

Scaled-generic musculoskeletal models were developed in OpenSim, an open-source 3D musculoskeletal modeling environment developed at Simbios (Delp et al., 2007), and from these models, single-leg landing simulations were generated (Fig. 1). The landing phase was defined from foot strike (0%) to maximum knee flexion (100%). A Matlab (The Mathworks Inc., Natick, MA) toolbox extracted the kinematic and kinetic data from C3D files and exported them into a suitable format for OpenSim. A Woltring filter (with a mean squared error of 15) and Butterworth filter with a 4th order, zero-lag, recursive filter with a cut-off frequency of 15 Hz were used for kinematics and kinematics data, respectively; and the outputs of these two filtering procedures were similar (mean RMS error $<$ 0.07 mm) (Kristianslund et al., 2012). Each model consisted of 10 segments with 23 degrees of freedom and 92 lower body muscle-tendon units (gait2392_simbody including the trunk) (Anderson and Pandy, 1999, 2001; Yamaguchi and Zajac, 1989). According to Laughlin et al. (2011), we scaled the maximum isometric muscle forces to twice of those used by Delp et al. (1990) to enable muscles to generate required joint torques during landing. After scaling the generic model to a given participant based on static trials and anthropometric measurements, a sequence of processing steps were employed to estimate muscle forces: inverse kinematics (the IK application within OpenSim), reduction of residual forces and moments (RRA) and static optimization (SO). The root mean squared (RMS) errors between RRA and IK kinematics were limited to match with similar modeling approaches (Table 1) (Hamner et al., 2010; Laughlin et al., 2011).

IK identified the joint angles that best fit the experimental motion capture data, RRA was subsequently used to obtain dynamically consistent joint angles (i.e., minimization of inconsistencies between measured GRF and measured kinematics), and finally, SO predicted muscle forces (using the RRA results) with the objective function being the minimization of the sum of squared muscle activations. Muscle force–length–velocity properties were taken into account and a Hill-type muscle model was used in this final step. Nonlinear SO method can predict co-contraction of pairs of multi-joint antagonists whereas this is not the case for pairs of one-joint antagonistic muscles (Ait-Haddou et al., 2000; Dorn et al., 2012; Herzog and Read, 1993; Jinha et al., 2006). Also, recently it has been shown that SO when compared to

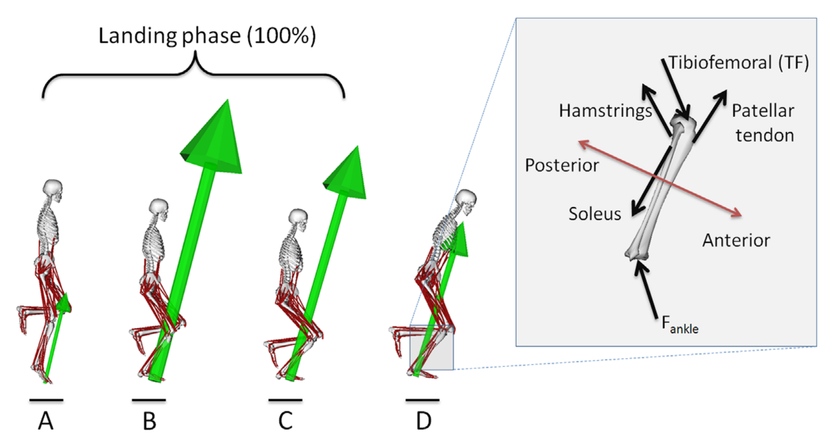

Fig. 1. Single-leg drop landing maneuver. A: foot strike, B: peak GRF, C: peak knee flexion angle, D: preparation for subsequent step (Left). Free body diagram of tibia. PT: patella force, TF: tibia femoral force, Hams: Hamstrings force, Fankle: ankle joint force (right).