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Research Article

The Effect of Medial Hamstring Weakness on Soft Tissue Loads during Running

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Abstract

Anterior cruciate ligament (ACL) reconstructions are frequently performed in the United States of America. The medial hamstrings graft has been shown to produce lower rates of osteoarthritis (OA) than the patellar tendon graft. The goal of this study was to determine how altering medial hamstring strength during surgery affects soft tissue loading, and hence the joint's proclivity towards OA. Muscle-actuated forward dynamic simulations of running were performed for normal muscle strength and decreased medial hamstring strength. The results show weakening the medial hamstrings caused an overall decrease in total hamstrings force by 7%, in total quadriceps force by 35%, and in cartilage contact force by 6%. This decreased force may be protective against long-term OA.

Introduction

Over 200,000 anterior cruciate ligament (ACL) reconstructions are performed every year in the United States [1], which leads to $15,000 in health care costs per procedure [2]. After ACL surgery, knee osteoarthritis develops within 10-20 years in 50% of these knees [3]. In an effort to reduce these long-term complications and associated health care costs, much research has been done on developing programs to prevent ACL injury [4], optimizing surgical techniques [5], and developing effective post-surgical rehabilitation programs [6]. One important surgical parameter to research is the tissue used to replace the ACL.

Typically, ACL reconstructions harvest ligament replacement tissue from two sites in the injured patient: patellar tendon and medial hamstrings [7]. Patellar tendon grafts are used in young athletes involved in dynamic sports because this graft allows for a quicker return to sport. However, donor site morbidity is an issue. Medial hamstrings grafts are preferred in young athletes due to smaller incisions for surgery and lower anterior knee pain, which results is lower donor site morbidity. Compared to a patellar tendon graft, patients receiving a medial hamstrings graft have reported a better ability to walk on their knees [8]. However, these studies are typically observational in nature, which precludes a mechanistic explanation of how the medial hamstrings graft affects joint health. The goal of our study is to determine how compromising the medial hamstrings affects joint health.

Joint health has been quantified as arthrokinematics measures, particularly cartilage contact forces. These forces have been shown to be associated with osteoarthritis progression [9]. Specifically, increased cartilage contact forces are positively related to increased rate of cartilage degradation [9]. Medial hamstrings grafts have been shown to result in a lower rate of osteoarthritis than patellar tendon grafts [10]. Hence, we hypothesize medial hamstring weakness (which results when harvesting the graft for reconstruction) will cause decreased cartilage contact forces during running. Running is an important exercise to investigate because 82% of athletes who receive an ACL reconstruction return to dynamic sporting activities [11].

Methods

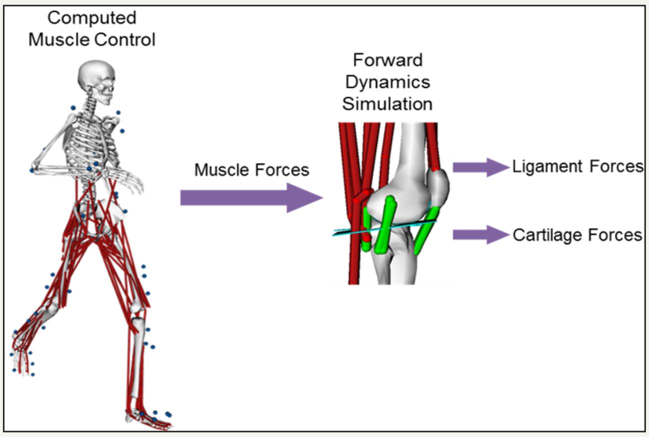

Figure 1: Serial approach where multi body dynamics are first solved using computed muscle control. The resulting muscle forces are used to actuate a discrete element knee model, where soft tissue loads are calculated.

Cartilage contact forces have only been measured *in vivo* using instrumented knee replacements [12]. This method is not available in patients with intact cartilage. Therefore, computational models are used to study soft tissue loads [13,14]. To quantify cartilage contact loads, an open-source musculoskeletal model of the body [15] and discrete element knee model [16] were utilized in a serial approach (Figure 1) [17,18].

First, a previously developed model of the entire body was used to perform a muscle-actuated forward dynamics simulation of running [15]. The model was comprised of 12 links representing bony segments of the body and 29 degrees of freedom (dof) for the joints. Each lower extremity contained 5 dof: ball-and-socket hip joints (3 dof), 1 dof custom knee joints, and revolute ankle joints (1 dof). Lumbar-pelvis motion was modeled as a ball-and-socket joint. Each arm was composed of 5 dof: ball-and-socket shoulder joints (3dof), hinge elbow joint (1 dof), and a revolute forearm joints (1 dof). Muscular structures were included as 92 musculotendon actuators and the arms moved using torque actuators at the shoulders. This model, along with experimental running kinematics and kinetics freely provided by [15], were input into computed muscle control (CMC) [19].

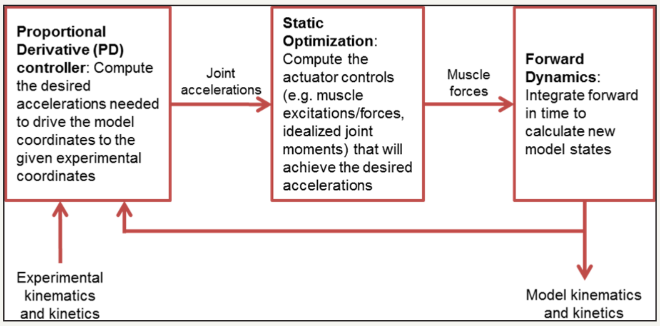

Figure 2: Computed muscle control (CMC) analysis used to calculate muscle forces needed to actuate a model to match experimentally measured kinematics and kinetics.

The CMC analysis is composed of three components: proportional-derivative (PD) controller, optimization, and forward dynamics (Figure 2). CMC calculates the muscle forces needed to actuate the model towards experimental kinematics and kinematics. The PD controller is used to determine if the predicted model motion is ahead or behind the experimental data and adjust accordingly. For example, if the model is ahead of the experimental data, the PD controller will accelerate the model to speed up. The PD controller ultimately calculates joint accelerations. The next component, optimization, is used to determine how to actuate the muscles to achieve these joint accelerations. Optimization is needed to reduce muscle redundancy, i.e. number of muscles is greater than the number of degrees of freedom. These muscle forces are then used in a short forward dynamics simulation to actuate the model forward by one time step. This new model location is compared to the experimental data, where the PD controller starts anew.

This muscle-actuated forward dynamics simulation of running was performed for two cases: normal muscle strength and weakened medial hamstrings. For the weakened hamstring model, the maximum isometric force of the semitendinosus and semi membranous were each decreased by 10% (Figure 3). The variables of interest extracted from these simulations were force in the medial hamstrings (semitendinosus and semimembranosus), lateral hamstrings (biceps long head and short head), and quadriceps (vastus lateralis, vastus intermedius, vastus medialis, and rectus femoris). The forces in all 92 muscles were subsequently used to actuate a discrete element knee model.

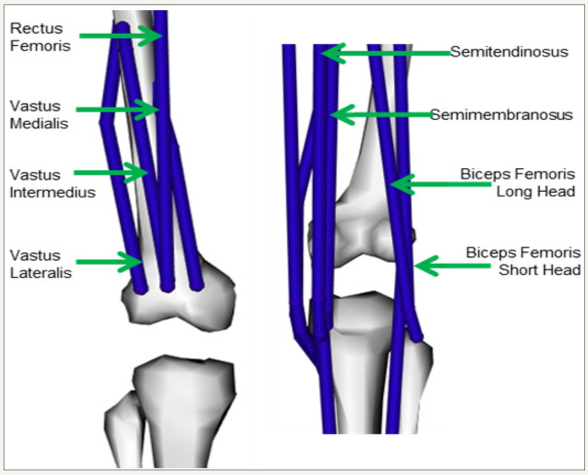

Figure 3 : Muscles of interest. The medial hamstrings were defined as the semitendinosus and semimembranosus. The biceps femoris long and short head were considered the lateral hamstrings.

The muscle forces from CMC were used to actuate a discrete element model using a forward dynamics simulation. The discrete element knee model consisted of a 6 dof tibiofemoral joint and 1 dof patellofemoral joint [16]. Knee motion was constrained via 18 non-linear elastic ligaments and contact. Contact was modeled as an elastic foundation model between the medial and lateral tibial plateaus and the femoral condyles. The geometry of the tibia was assumed to be planar and the femur geometry taken from MRI data. The muscles included in the discrete element knee model were the same as those from the whole body model [15].

Forward dynamics was used actuate the discrete element knee model with the CMC results of the whole body model. The discrete element knee model was modified for the two cases: normal muscle strength and weakened medial hamstrings. The variables of interest extracted from these forward dynamics simulations were force magnitude in the medial tibiofemoral compartment and lateral femoral compartment. Muscle and cartilage contact forces were compared to test the study hypothesis: medial hamstring weakness will cause decreased cartilage contact forces during running.

Results

Decreasing the medial hamstring strength by 10% resulted in increased peak force for the semitendinosus by 8% (medial hamstring) and biceps femoris long head by 2% (lateral hamstring) (Table 1 & Figure 4). In contrast, a decreased peak force was experienced by the semimembranosus by 11% (medial hamstring) and biceps femoris short head by 4% (lateral hamstring). Ultimately, weakening the medial hamstrings caused an overall decrease in total hamstrings force by 7%. Peak force was also decreased for all of the quadriceps muscles by 27-45%, with a decrease of 35% for the total quadriceps force (Table 2 & Figure 4). The maximum forces in the medial and lateral tibiofemoral cartilage were decreased by 7% and 2%, respectively, after the medial hamstrings were weakened (Table 3 & Figure 5). This resulted in a 6% decrease of the total contact force.

Table 1: Change in maximum hamstrings force.

	Semitendinosus	Semimembranosus	Biceps Femoris Long Head	Biceps Femoris Short Head	Total Hamstrings Force
Normal	221	601	493	471	1783
Weak	238	542	502	453	1669
% Change	8	-11	2	-4	-7

*all force values expressed in Newtons.

Table 2: Change in maximum quadricpes force.

	Vastus Medialis	Vastus Lateralis	Vastus Intermedius	Rectus Femoris	Total Quadriceps Force
Normal	999	2038	1193	998	4268
Weak	723	1520	825	787	3170
% Change	-38	-34	-45	-27	-35

*all force values expressed in Newtons.

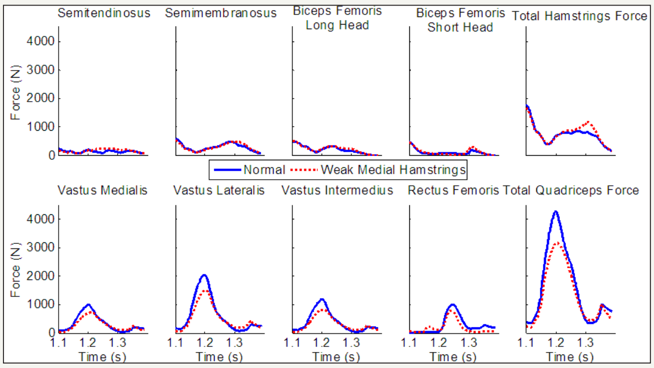

Figure 4: Effect of medial hamstring weakness of quadriceps and hamstrings forces.

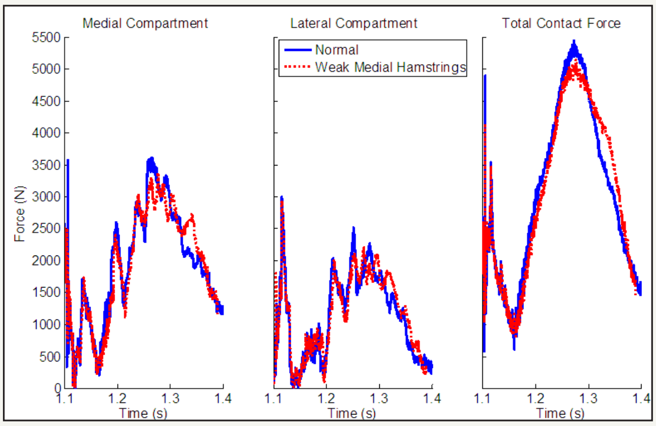

Figure 5 : Effect of medial hamstring weakness of cartilage contact forces.

Table 3: Change in maximum cartilage contact force.

	Medial	Lateral	Total Contact Force
Normal	3612	2999	5450
Weak	3376	2928	5145
% Change	-7	-2	-6

Discussion

In ACL reconstruction surgery, graft tissue is harvested from the medial hamstrings. This causes donor site morbidity but a decrease in osteoarthritis occurrence, compare to patellar tendon grafts. The goal of this study was to develop a mechanistic explanation for how a medial hamstrings graft would affect joint health. Muscle-actuated forward dynamics simulations of running were used to calculate muscle forces and cartilage contact loads for a healthy knee and a model with decreased medial hamstrings strength.

Ultimately, weakening the medial hamstrings caused an overall decrease in total hamstrings force by 7% and in total quadriceps force by 35%. This can be explained using a free body diagram of a sagittal view of the knee (Figure 6). In both the normal and weakened simulations, the same amount of sagittal plane torque to flex and extend the knee was produced. When the medial hamstrings were weakened, the quadriceps muscles were more affected than the hamstrings. Since the quadriceps have a larger flexion/extension moment arm than the hamstrings, the flexion/ extension torque is more sensitive to alterations in quadriceps force. This agrees with other studies that have shown quadriceps weakness and dysfunction in those with ACL reconstructions [20].

The decrease in muscle forces resulted in a total decrease in cartilage contact force by 6%. Since increased force has been shown to expedite cartilage degeneration, this decreased cartilage load may help explain the low rates of osteoarthritis in those with a medial hamstring graft [10]. Although, some level of mechanical loading is needed for cartilage growth and remodeling [21]. Therefore, more work is needed to better elucidate the balance between too little loading that can cause atrophy versus too much loading that can cause degeneration.

In summary, musculoskeletal modeling was used to quantify the distribution of soft tissue loads when the medial hamstrings are compromised, which is common in ACL reconstructions. Overall, muscle forces decreased with the quadriceps more affected than the hamstrings. Cartilage contact loads also decreased, which may have implications for joint health and long-term OA development. The next step in this study is to elucidate the optimal loading needed to maintain cartilage health.

Acknowledgement

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