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WHICH MUSCLES HAVE THE GREATEST POTENTIAL TO ALTER PEAK TIBIOFEMORAL FORCES DURING WALKING?

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INTRODUCTION

The tibiofemoral (TF) joint is subjected to intense mechanical loads that affect the health and function of the knee. These large loads have been associated with degeneration [1] and pain [6] in the knee. Training and rehabilitation programs have reduced TF loads during walking [4], but these programs have primarily focused on altering gait kinematics. The effects of altered muscle coordination on TF loads remain unclear.

The purpose of this study was to determine the sensitivity of TF forces to variations in muscle coordination. Specifically, our goal was to identify the muscles with the greatest potential to alter the peak TF force during walking.

METHODS

We created a musculoskeletal simulation of walking based on gait data obtained from the ASME Grand Challenge Project [5]. These data include marker positions, ground reaction forces, and *in vivo* TF forces measured from one subject (83 year old male, 64 kg, 166 cm tall, 1.3 m/s) implanted with an instrumented total knee replacement (TKR). The instrumented TKR measured compressive TF force normal to the tibial plateau.

To compute TF forces during walking, we adapted a generic musculoskeletal model [2] composed of 10 segments, 19 degrees of freedom, and 92 muscle-tendon units in OpenSim [3] (Figure 1A). We refined the knee model of the generic musculoskeletal model so that accurate resultant forces at the TF joint could be computed. We scaled the modified model to match the mass and segment lengths of the experimental subject. We performed an inverse kinematics analysis to compute joint kinematics of the model during a walking trial.

We determined individual muscle forces using a static optimization analysis that minimized the weighted sum of squared muscle activations (Equation 1).

$$\min\left[\sum_{i=1}^{nMuscles}(w_i a_i)^2\right] \quad \text{Equation 1}$$

In Equation 1, a_i was the activation of the i^{th} muscle, and w was an activation weighting constant. To investigate the sensitivity of TF forces to activation of a muscle, we ran multiple static optimizations with w for that muscle adjusted between 0 and 100, while w of all other muscles was held at 1. A w = 0 represented no penalty to activate a muscle during walking, while w = 100 prohibited activation of a muscle. Each static optimization generated a muscle coordination strategy that reproduced the measured gait dynamics and computed the resulting TF forces. We obtained the range of TF forces resulting from varying w for each muscle of the lower limb.

We measured the potential for a muscle to alter peak TF force during walking by calculating the difference in peak TF forces when its activation was prohibited (w = 100) and when it was allowed to activate without penalty (w = 0). We measured changes in peak TF force during early stance (0 to 33% of gait cycle), late stance (33 to 66% of gait cycle), and the complete gait cycle.

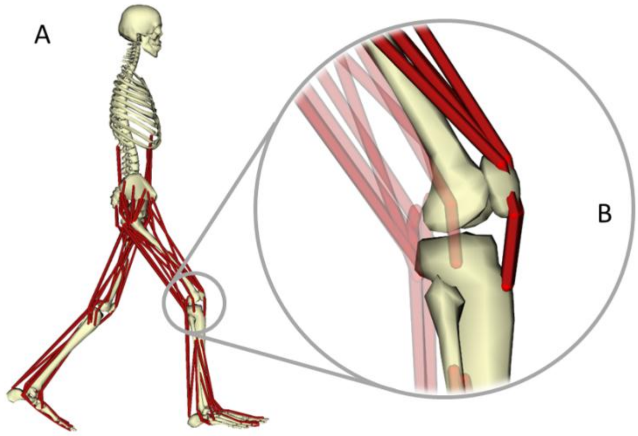

Figure 1. (A) Musculoskeletal model of the human legs and torso, including a refined knee mechanism (B).

RESULTS AND DISCUSSION

Tibiofemoral forces were sensitive to activations of individual muscles of the lower limb, especially during the late stance phase of walking (Figure 2). Varying activations of the gluteus medius muscle produced large changes in TF forces throughout stance phase, with a maximum range of 5.4 bodyweights at 44% of the gait cycle. Tibiofemoral forces were sensitive to activations of the gastrocnemius (maximum range 3.8 bodyweights) and the rectus femoris (maximum range 3.2 bodyweights), but only during the late stance phase. Tibiofemoral forces were also sensitive to activations of the psoas major, iliacus, and soleus muscles during the late stance phase. Tibiofemoral forces were minimally sensitive to activations of the vasti.

Increased activation of the gluteus medius muscle produced the largest decrease in peak TF force during late stance (Figure 3). A similar effect was observed for the psoas, iliacus, and soleus muscles. In contrast, increased activation of the gastrocnemius muscle produced the largest increase in peak TF force during late stance. A similar effect was observed for the rectus femoris and the biceps femoris short head muscles. Changes in individual activations of other muscles of the lower limb, including the vasti, had minimal effect on peak TF force during late stance. Peak TF forces during early stance (not shown) were less sensitive to selective activation of individual muscles (less than one bodyweight).

Our study demonstrated that varying activations of the gluteus medius, a muscle crossing the hip joint, had the largest effect on TF forces during walking. While the gluteus medius, psoas, iliacus, and soleus muscles do not cross the knee, increasing their activations resulted in decreased activations in muscles that do cross the knee. Conversely, increasing activations of the vasti muscles, the largest muscles crossing the knee joint, had minimal effect on TF forces during walking due to compensatory activations of the rectus femoris muscle.

Our study suggests that an individual may adopt muscle coordination strategies that decrease TF forces during the late stance phase of walking. We assumed that changes in muscle activations did not cause kinematic compensations, thus the walking motion was unchanged. Other studies have demonstrated that altered walking kinematics also decrease TF loads [4,7]. It may be feasible to combine kinematic gait retraining with muscle coordination and strength training to design interventions that decrease TF forces throughout the gait cycle of walking.

CONCLUSIONS

We found that TF forces during walking were sensitive to activations of a small subset of important muscles. Tibiofemoral forces were most sensitive during the late stance phase, when varying activations of the gluteus medius, gastrocnemius, or rectus femoris muscles changed TF forces by several bodyweights.

Our study suggests that inactivity or weakness in the muscles crossing the hip joint can adversely affect the health of the knee joint. Increased activation and strength of the gluteus medius, psoas, and iliacus muscles, as well as the soleus muscle can decrease TF forces and promote the health of the knee joint. Training programs targeting knee rehabilitation should include exercises that strengthen the muscles crossing the hip joint and promote hip muscle activity during walking.

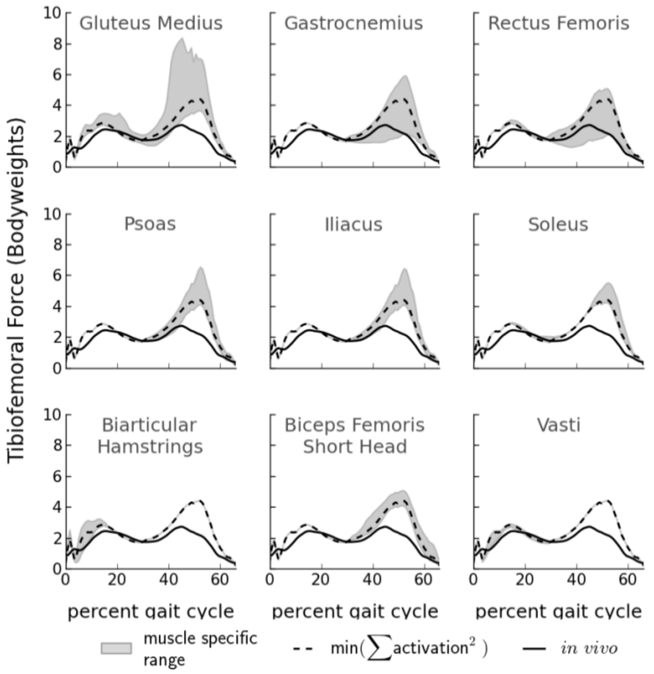

Figure 2. The effect of varying activation of individual muscles or muscle groups on predicted tibiofemoral forces shown for the most influential muscles.

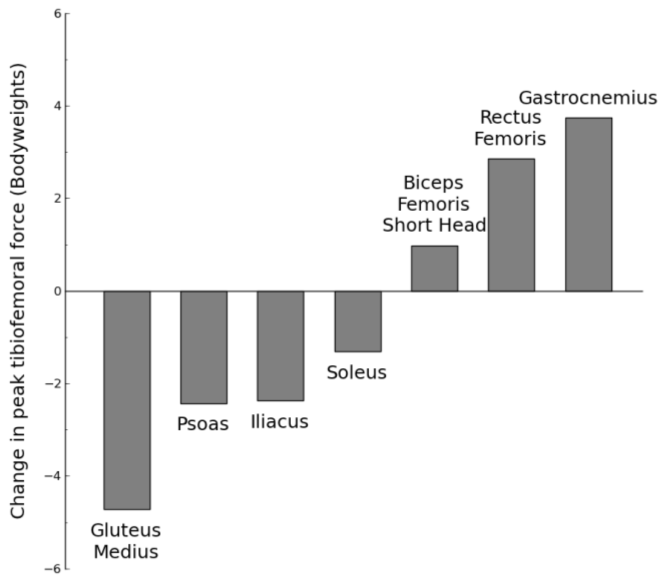

Figure 3. Maximum change in peak tibiofemoral force due to activation of a muscle or muscle group during the late stance phase of walking (33 to 66% gait cycle).

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