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Hamstrings and quadriceps muscle contributions to energy generation and dissipation at the knee joint during stance, swing and flight phases of level running

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ABSTRACT

Background: Human movements involve the generation and dissipation of mechanical energy at the lower extremity joints. However, it is unclear how the individual knee muscles contribute to the energetics during running.
Objective: This study aimed to determine how each hamstring and quadricep muscle generates and dissipates energy during stance, swing and flight phases of running.
Methods: A three-dimensional lower extremity musculoskeletal model was used to estimate the energetics of the individual hamstrings (semimembranosus, semitendinosus, biceps femoris long and short-heads) and quadriceps (rectus femoris, vastus medialis, vastus intermedius and vastus lateralis) muscles for a male subject during level running on a treadmill at a speed of 3.96 m/s.
Results: Our findings demonstrated that the knee flexors generated energy during stance phase and dissipated energy during swing phase, while the knee extensors dissipated energy during the flexion mode of both stance and swing phases, and generated energy during the extension mode. During flight phase, the knee flexors generated energy during the flight phase transiting from toe-off to swing, while the knee extensors generated energy during the flight phase transiting from swing to heel-strike.
Conclusion: Individual knee flexors and extensors in the hamstrings and quadriceps play important roles in knee joint energetics, which are necessary for proper execution and stabilization of the stance, swing and flight phases of running.

1. Introduction

Human lower extremity movements primarily involve the generation and dissipation of mechanical energy at the hip, knee and ankle joints. These processes of energy generation and dissipation are typically considered as positive and negative work done by the joint musculature respectively. Prior studies have shown that movements, such as drop-landing, tend to give rise to energy dissipation as the joint muscles are employed to maximize shock absorption in response to the landing impact [1,2]. On the other hand, movements like walking and running, require propulsion and therefore are biased towards energy generation [3,4].

Among the lower extremity joints, the knee joint is known to be an important shock absorber [2,5,6] and is also highly susceptible to injuries sustained during lower extremity movements, which can include cartilage damage due to repetitive stress injuries [7] and anterior cruciate ligament injuries [8]. While the knee joint musculature serves a crucial role in energy dissipation in the presence of impact loading, it is also capable of generating energy and providing propulsion [4].

Running is a cyclic movement that involves the stance, swing and flight phases. Prior studies have shown that the hamstrings and quadriceps muscle groups have different roles during the stance and swing phases of running, which help to provide stability and forward motion [9–11]. However, the contributions of the individual knee flexors and extensors in these muscle groups to the overall energy dissipation and generation strategy are unknown. Moreover, it is unclear how these individual muscles contribute to the knee energetics during flight phase.

Therefore, this study sought to determine how the individual hamstrings muscles (semimembranosus, semitendinosus, biceps femoris long and short-heads) and quadriceps muscles (rectus femoris, vastus medialis, vastus intermedius and vastus lateralis) generate and dissipate energy during the stance, swing and flight phases of running, using a three-dimensional lower extremity musculoskeletal model.

2. Materials and methods

2.1. Subject data

Subject motion analysis data were obtained from an online repository (SimTK.org, Simbios National NIH Center, USA). The subject was

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a healthy male (age: 30 years old; height: 1.83 m; mass: 65.9 kg) and was instructed to run on a treadmill with a speed of 3.96 m/s. Forty-one markers were placed on the subject's body, according to the marker system developed by Kadaba et al. [12]. Marker trajectories and ground reaction forces (GRF) during running were captured using a six-camera motion capture system (Motion Analysis Corporation, Santa Rosa, CA, USA) and a force-plate instrumented treadmill (Bertec Corporation, Columbus, OH, USA), with corresponding sampling rates of 60 Hz and 600 Hz, respectively. All kinematics and kinetics data were filtered with a finite impulse response low pass filter at a cut-off frequency of 20 Hz.

2.2. OpenSim model

A three-dimensional lower extremity musculoskeletal model was used to estimate the knee muscle energetics of a subject during level running (Fig. 1). The model comprises of 92 actuators to act as the lower extremity musculature. The locations of the muscle origins and insertions in relation to the bone segments of the model were designated based on prior experimental studies [13–15]. The lumbar motion and hip are modeled as ball-and-socket joints with three degrees-of-freedom [16], while both the knee and ankle are modeled with one degree-of-freedom in the sagittal plane [15,17]. Based on the marker placement on the subject, the musculoskeletal model was scaled accordingly. In addition, the model takes into consideration the neighboring structures such as the hip joint and pelvis, as hip joint motion during running will likely affect the muscle energetics at the knee joint. The semitendinosus, semimembranosus, biceps femoris long head and rectus femoris were modeled such that the origins of these knee muscles were attached to the pelvis. Kinematic changes in the hip joint were introduced into the model using experimental data of pelvic marker trajectory collected through motion capture of the running trials.

2.3. Running simulation

An inverse kinematics step was performed to determine appropriate joint kinematics that reduce the difference between actual marker positions on the subject and virtual marker positions on the model. Subsequently, a residual reduction tool was implemented, which slightly alters the model mass properties and model kinematics to improve dynamic consistency between kinematics and GRF data [18]. In order to estimate muscle activations, a computed muscle control tool was introduced [19,20]. This tool uses a static optimization approach, which computes muscle excitations that will drive the musculoskeletal model to track the desired kinematics in the presence of GRF, obtained from the prior residual reduction step. Accuracy of the simulation was verified in a prior study [21], which compared (1) simulated kinematics and kinetics data with experimental literature data, (2) simulated muscle activation data with the subject's recorded EMG, and (3) simulated muscle forces with previous musculoskeletal models on running.

2.4. Data analysis

The muscles of interest are the quadriceps and hamstrings groups. The quadriceps comprise of the knee extensor muscles, namely rectus femoris, vastus medialis, vastus intermedius and vastus lateralis, while the hamstrings comprise of the knee flexor muscles, namely semimembranosus, semitendinosus, biceps femoris long and short-heads. The mechanical power outputs of these muscles were analyzed over the stance, swing and flight phases of the subject's running gait cycle. Mechanical work done by the muscles was calculated by the time integral of the power. Positive work indicates energy generation by the muscles while negative work refers to energy dissipation by the muscles. All energetics data were normalized to the subject's body mass.

3. Results

3.1. GRF and knee kinematics

The vertical GRF profile indicates a typical running gait (Fig. 2A) and determines the stance and swing phases for both left and right legs. For both legs, the peak knee flexion angle was larger (left: 95.3°, right: 105.1°) during swing phase than during stance phase (left: 57.3°, right: 50.0°) (Fig. 2B). These peaks were used to demarcate the flexion and extensions modes of the stance and swing phases; these modes referred to the duration wherein the knee joint was flexing or extending.

3.2. Knee flexor energetics during stance and swing phases

For both left and right legs, the hamstrings power was generally negative during swing phase and positive during stance (Fig. 3A). The semimembranosus and semitendinosus exhibited distinct negative power peaks during swing phase for both left and right legs (Fig. 4A and B), while the biceps femoris long and short-heads displayed prominent positive power peaks during stance phase for both left and right legs (Fig. 4C and D).

In terms of work, the semimembranosus, semitendinosus and biceps femoris long-head were the dominant energy generators during the flexion mode of the stance phase, while the biceps femoris long and short-heads were the major energy generator and dissipator respectively during the extension mode of the stance phase (Table 1). The semimembranosus and semitendinosus were the key energy generator and dissipator respectively for the flexion mode of the swing phase, and both of these

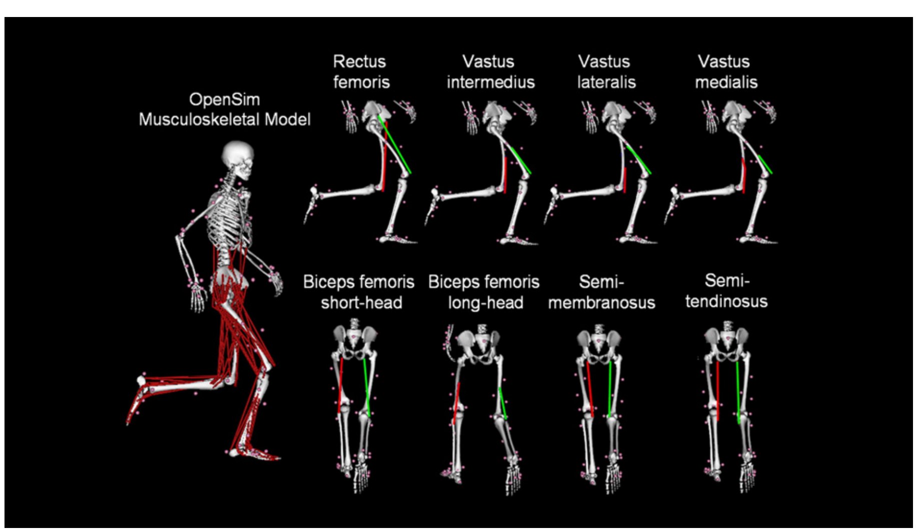

Fig. 1. The OpenSim musculoskeletal model, used in the current study, shows the knee muscle attachments to the tibia, femur and pelvis for the quadriceps (rectus femoris, vastus intermedius, vastus lateralis and vastus medialis) and hamstrings (biceps femoris short-head, long-head, semimembranosus and semitendinosus).