Crouched Posture Maximizes Ground Reaction Forces Generated by Muscles

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INTRODUCTION

Crouch gait, a common movement abnormality among children with cerebral palsy, decreases walking efficiency due to the increased knee and hip flexion during the stance phase of gait [1]. Excessive knee flexion during walking can deteriorate joints and may lead to chronic knee pain [2], and if untreated, these symptoms could worsen over time [3]. Several factors have been linked with crouch gait, including muscle weakness, spasticity, tightness, and decreased motor control [4]. Despite being studied for decades, a cause-and-effect relationship between these factors and crouch gait remains unknown, in part, due to the complexity of the musculoskeletal system [4].

Crouch gait is generally considered to be disadvantageous for patients with cerebral palsy; however, a crouched posture may afford biomechanical advantages that lead some patients to adopt a crouch gait. For example, an athlete adopts a crouched posture to increase the ability to move in any chosen direction. Likewise, a passenger standing on a moving train adopts this posture to increase the ability to resist moving. In both cases, the transverse-plane movements are produced or resisted by generating ground reaction forces in the transverse plane.

In this study, we used musculoskeletal modeling and optimization to investigate one possible advantage of crouch gait. Our previous study showed that the crouched posture during middle stance allowed the largest ground reaction force profile [5]. Our goal for this study was to extend the previous study to determine if posture influences the muscles' capacity to generate ground reaction forces in the transverse plane throughout the stance phase of gait. We hypothesized that a crouched posture allows the largest area of force profile among postures from upright to severe crouch (Figure 1). The results of this study suggest one advantage to adopting a crouched posture is an increased capacity of ground reaction forces to compensate for impairments associated with cerebral palsy.

METHODS

A three-dimensional musculoskeletal model with 15 degrees of freedom and 92 muscle-tendon actuators was created in OpenSim [6]. The model consists of a head, trunk, pelvis, and right and left femur, tibia, and foot segments. The stance foot (right foot in our case) was welded to the ground. The lower extremity joints were modeled as follows: the subtalar and ankle joint were revolute joints, each knee was a planar joint, and the hip was a ball-and-socket joint. The head and torso were included in the model and were articulated with the pelvis through a ball-and-socket joint.

The musculoskeletal model was placed in 15 different postures from upright to severe crouch during initial, middle, and final stance of the gait cycle for a total of 45 postures (Figure 1). Upright posture was defined from the average gait data of 83 able-bodied subjects [7]. Crouch was defined from the average gait data of 100 subjects with cerebral palsy and crouch gait [7]. Using this experimental data, we linearly interpolated nine postures between upright and crouch for the three different parts of stance. We extrapolated four additional postures with knee flexions greater than crouch as well.

For each of the 45 different postures, a series of optimizations were performed. The optimizer maximized ground reaction forces for the 8 compass directions in the transverse plane by modifying muscle forces acting on the model. Each optimization was subject to constraints requiring: 1) the center of pressure to be under the stance foot and 2) the vertical ground reaction force to be greater than or equal to zero. A ground reaction force profile was generated for each posture by finding the area of the forces from the 8 compass directions. Our hypothesis was evaluated by comparing the areas of the force profiles across all postures.

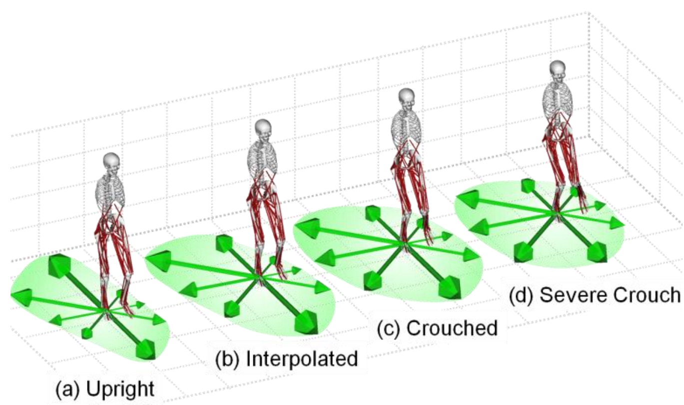

Figure 1: Three-dimensional, full-body musculoskeletal model with 15 degrees of freedom and 92 muscle-tendon actuators placed in 4 (of 45 total) postures shown with maximum ground reaction force profiles in the transverse plane: (a) experimental upright posture [7], (b) interpolated posture between experimental upright and crouch data, (c) experimental crouched posture [7], (d) and extrapolated posture from experimental upright and crouch data.

RESULTS AND DISCUSSION

A range of crouched postures allowed the largest areas of ground reaction force profiles during stance (Figure 2). Before middle stance, mild crouched postures (#4-6) between upright and crouch allowed the largest ground reaction force profiles. These postures produced force profile areas within 1% of each other, with posture #5 being the largest. Comparatively, upright (#1) and crouched (#11) postures had 12-13% smaller force profile areas, and severe crouch (#15) was roughly 23% smaller. From our previous work, the crouched posture during middle stance produced the largest area of force profile [5]. This trend continues until final stance. During final stance, a posture (#12) between crouch and severe crouch allowed the largest ground reaction force profiles; however, this force profile area was less than 2% larger compared to crouch (#11). The force profile area of crouch was 7.3% higher compared to upright and 4% higher than severe crouch during final stance.

This study examined how ground reaction forces generated by muscles change as a function of posture. We found that the force profile area for initial stance was highest between upright and crouched postures and dramatically decreased as postures approached upright or crouch. During middle stance, we previously reported that the force profile area of crouch was 24% larger than upright and 8% larger than severe crouch [5]. The trend for final stance was similar to results for middle stance with the exception that upright posture allowed higher forces compared with mild crouch.

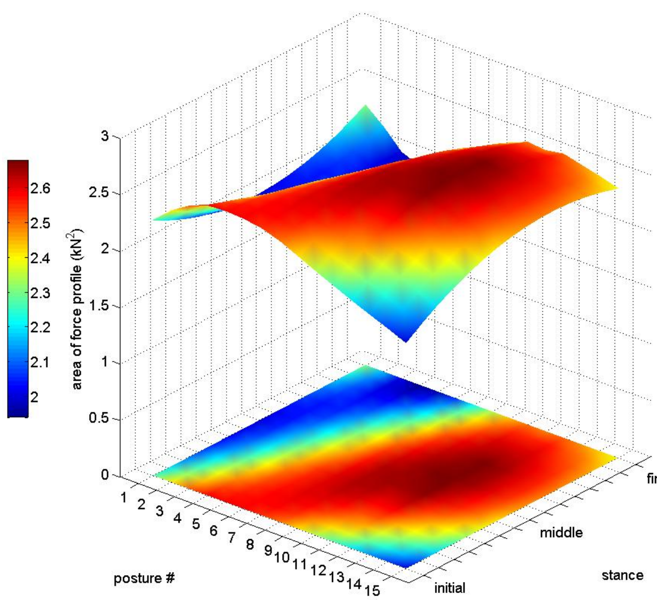

Figure 2: Areas of ground reaction force profiles across three parts of stance and across all postures (intermediate force profile areas between initial-middle-final generated with a cubic spline interpolation). Force profile areas throughout stance are from lowest (blue) to highest (red). During early stance, mild crouched postures (#4-6) allowed the greatest forces. During late stance, crouched postures (#9-11) allowed greater forces compared to upright.

An overall larger force profile area is allowed by postures from mild crouch (for initial stance) to crouch (for final stance). To maximize the muscles' capacity to generate ground reaction forces in the transverse plane, one would have to move from a mild crouch to a crouched posture throughout the stance phase of gait (Figure 2, red areas).

Although this study extends our previous study [5], this work is fundamentally different from Hicks et al. [7] which examined the effect of crouched postures on the capacity of muscles to extend the hip and knee joints. They used induced acceleration analysis to determine the joint angular accelerations towards extension resulting from the application of 1 N muscle force to the model. Their study showed almost all of the major hip and knee extensors' capacities were reduced in crouch gait. This finding suggests a reduction in the ability to generate *vertical* ground reaction force. In our case, we used optimization to maximize *horizontal* ground reaction forces without regard for the *vertical* ground reaction force. Our finding suggests an increase in the ability to generate these *horizontal* forces.

CONCLUSIONS

The overall ability to generate larger ground reaction force profiles represents a mechanical advantage of a crouched posture. This advantage results from increased capacity of muscles to generate ground reaction forces. This increase in muscle capacity while in a crouched posture may allow a patient to generate new movements to compensate for impairments associated with cerebral palsy, such as motor control deficits.

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