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Femur Abduction Associated with Transfemoral Amputation Alters the Profile of Lumbopelvic Mechanical Loads During Generalized End-Limb Loading

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Abstract—**Pain in the lower back is frequent problem for most individuals with transfemoral amputation, which limits their overall mobility and quality of life. While the underlying root causes of back pain are multifactorial, a contributing factor is the mechanical loading environment within the lumbopelvic joint. Specifically, this study aims to explore the upstream effects amputation has on the mechanical loading environment of the lumbopelvic joint using a 3D musculoskeletal model of transfemoral amputation. A generic musculoskeletal model was altered to represent a transfemoral amputation. Muscle parameters were adjusted to represent a myodesis amputation surgery that preserved musculotendon tension in a neutral anatomical pose. The model contained a total of 28 degrees of freedom and 76 muscles spanning the lower-limb and torso. In forward dynamics simulations, generalized external forces were applied to the distal end of the residual limb at a series of directions. Axial, oblique and transverse 10 N end-limb loads were applied. In addition, simulations were performed for 0°, 4°, and 8° of femur abduction, which are clinically observed in individuals with transfemoral amputation. In these simulations, reaction forces and moments at the lumbopelvic joint were computed. In general, femur abduction had little effect on back loading for an axial applied end-limb force. These data showed that while the individual magnitudes of lumbopelvic force and moment reactions did not significantly deviate for differing levels of femur abduction, the pattern of how these forces changes in response to different end-limb force directions (applied circumferentially along the limb) was affected by femur abduction angle.**

Clinical Relevance— **The changes in joint reaction forces in the lumbopelvic joint from an aligned position to an abducted position reinforce the importance of avoiding hip flexion-abduction contracture during amputation surgery. This suggests that surgical techniques such as myodesis, osseointegration, or medial thighplasty, which intend to maintain anatomical alignment may have beneficial upstream effects for the patients during locomotion. Given the prevalence of lower back pain in individuals with transfemoral amputation, teasing out the causes of lower back pain could bring relief to a population that struggles with community independence.**

I. Introduction

Pain within the lower back is reported as being a major contributor to the degradation of quality of life in individuals with lower limb amputations, further diminishing the ability of these individuals to return to fully functioning lifestyle. More than 60% of individuals with lower limb amputation experience chronic back pain and specifically 80% of individuals with transfemoral amputations [1]. Explorations of the potential factors leading to lower back pain in this group of individuals could lead to innovations to eliminate or mitigate this amputation-associated pain.

There are many factors that could potentially cause back pain in this group of people. Adaptive gait and gait asymmetries in the trunk and the lumbopelvic region have been observed in individuals with transfemoral amputation by researchers, particularly during the stance phase of gait [2]–[7]. Additionally, postural asymmetries have been shown to lead to an increased risk for lower back pain in healthy limbed adolescents; weakened or missing hip muscles in individuals with transfemoral amputation have been theorized to lead to postural asymmetries [8],[9]. Pelvic tilt and lumbar extension have been observed in studies of individuals with transfemoral amputation, both of which could lead to postural asymmetries and overloading in the lumbar [7],[10]. These abnormalities in the lumbar region are thought to be results of altered biomechanical forces expressed upstream as the body attempts to compensate for distal use of a prosthetic limb.

Beyond the misalignment arising from abnormal movement in the trunk and lumbopelvic region, individuals with transfemoral amputation have weakened hip adductor muscles, which can lead to hip contracture. Several surgical techniques have been developed to mitigate the effects of hip contracture. Myodesis involves suturing the severed ends of a selection of muscles on the medial and posterior side of the femur, anchoring those muscles to the bone and thereby preserving tension, and discouraging a flexed and abducted femur in a neutral pose. In addition, osseointegration is a prosthetic attachment technique that attaches the pylon of the device directly to the amputated femur through an abutment. While the primary benefit of osseointegration has been proposed eliminating the need to wear a prosthetic socket, another significant benefit is the ability to maintain a proper anatomical alignment of the femur. Finally, medial thighplasty is plastic surgery technique which recontours and resurfaces the limb, which has been recently evaluated as it was applied to the limb of an obese individual with transfemoral amputation. The technique removes excess fatty tissue and skin primarily from the medial portion of the thigh, which was shown to improve femur alignment during weight

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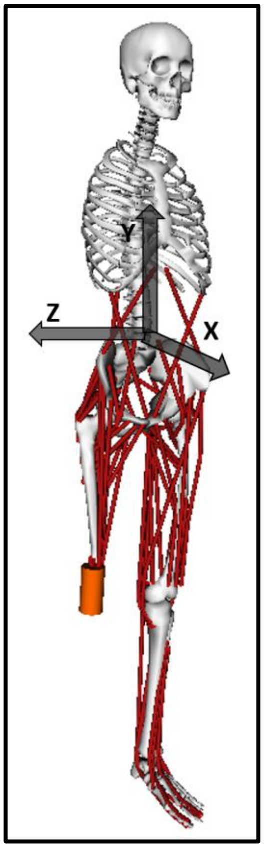

Figure 1: The OpenSim model of a transfemoral amputee used in this study consisted of modified kinematic degrees of freedom, muscle lines of action, and musculotendon parameters relative to a generic non-amputee model. In the simulation, end-limb forces were applied in axial, oblique and transverse directions to the distal end of the prosthetic pylon segment (shown in orange).

bearing with a prosthesis [11]. All of these surgical techniques incorporate the goal of preserving the anatomical alignment of the amputated limb and avoid hip contracture.

In our study, we use a recently developed musculoskeletal model of a transfemoral amputation, performed using an adductor myodesis technique. The purpose of this study was to use a musculoskeletal modeling approach to explore how the joint reaction forces in the lumbopelvic joint change with abduction of the residual limb femur and as well as the direction of end-limb forces. Specifically, we tested axial, oblique, and transverse end-limb forces that were applied circumferentially at the distal end of the residual limb that were chosen to represent varying forms of standing and overground locomotion. We hypothesized that increased abduction of the femur would produce greater increased joint reaction forces and moments of the lumbopelvic joint, and that oblique end-limb forces that more closely represent loading during ambulation would exacerbate these effects.

II. Methods

A. Model Design

In this study, we used a musculoskeletal modeling approach to estimate internal forces of skeletal joints, which would be nearly impossible to directly measure in an experimental setting [12]. Using a computer model also enables the ability to impose repetitive loading scenarios without causing harm or discomfort to a test subject. While the data produced is specific to a generic model, it provides a baseline of musculoskeletal interactions that can be built upon to inform future experiments. The model (Fig. 1) used in the study was adapted from a previous study on transfemoral amputation with myodesis surgical technique [13]. This model consists of 28 degrees of freedom, and 76 muscles across 9 joints, although the 3 translational degrees of freedom for the pylon as well as the 4 degrees of freedom for the intact ankle and metatarsophalangeal joint were locked, leaving 21 degrees of freedom in these simulations.

B. Forward Dynamics Simulations

To evaluate the reaction forces in the lumbar when external end-limb forces are applied, a series of simulations were executed. A static motion file (i.e., all degrees of freedom in their neutral position) was used to perform forward dynamics simulations where an external force of 10 N was applied to the distal end of the pylon. The simulations lasted 300 ms and were repeated for 8 directions (every 45°) surrounding the pylon on three planes: transverse, 45° oblique, and vertical or axial (Fig 1). These simulations were repeated for three femur abduction levels: 0°, 4°, and 8°, where 0° refers to the anatomically neutral position, resulting in 48 simulations. Computed muscle control optimization was used to solve for the muscle forces necessary to maintain the model in its neutral position. The muscle force data were then used as input to joint reaction analysis. The final products of these analyses were data on the internal joint reaction forces and joint reaction moments of the 6 DOF lumbopelvic joint.

III. Results

The simulations showed a change in the profile of joint reaction forces and moments per direction from 0° to 4° and 8° of limb abduction, but only did so for external oblique forces (Fig 2 and 3). However, there was no noticeable difference between 4° and 8° abduction joint forces. The change in profile differed in each direction, rather than an overall increase or decrease in joint reaction forces. Joint reaction forces in response to medial and medial-posterior external forces remained relatively constant across abduction levels, but joint reaction forces in response to posterior external forces differed greatly, suggesting back loading during tasks that require opposing a posteriorly-directed end-limb force (such as during the loading response phase of gait) are affected by femur abduction angle. Joint reaction forces in response to transverse end-limb forces showed no sensitivity to limb abduction angle. Likewise, external axial forces and their contribution to back loading did not seem to be affected by femur abduction.

IV. Discussion

This research shows the effect that an abducted femur has on lumbar loading during generalized end-limb loading in a musculoskeletal model of transfemoral amputation. We hypothesized that abnormal lumbar loading is a contributor to abnormal back loads, which are relevant as a potential cause of lower back pain. Furthermore, femur abduction has been known to be occur as a result of transfemoral amputation. Several studies have also noted increased motion on the frontal plane during gait in transfemoral amputation as compared to control groups, which could be due to non-aligned femur [4], [5], [14], [15].

A. Biomechanics associated with Low Back Pain

While a definitive biomechanical cause of back pain has not been established, studies have suggested various contributing factors including asymmetrical gait, lordosis, trunk sway, and postural asymmetries. In a study by Rabuffetti et al, a significant amount of pelvis tilt was observed during gait. They attributed the tilt to compensation method to maintain normal gait [7]. However, we observed peaks of loading in the lumbar in response to external forces, which suggests that the pelvic tilt can be attributed to the mechanics of the musculoskeletal system. Nakipoglu et al. found a significant relationship between lumbar shape and stability [16]. Specifically, they saw that adolescents with lordosis were predisposed to lower back pain later in life. We observed an increase in anterior joint reaction moments, which could be expressed as an anterior pelvic tilt and lordosis if larger external forces were applied. Although at the force levels we used, the pelvis remained neutral.

B. The Role of External Force Orientation

The differential manner in which the joint reaction forces change with abduction level suggests a correlation between femur alignment and forces in the lumbar. The decrease in joint reaction forces for certain directions maybe due to the altered insertion positions of the muscles due to myodesis surgical technique. To prevent hip contracture, severed muscles are reattached to the medial and posterior femur, with the goal of pulling the femur back into the anatomical axis [17]. This change in insertion point changes the mechanics of some of the severed muscles and leads to a situation where the hip abduction and flexion moment arm of these muscles is smaller.

C. The Importance of Skeletal Alignment

As stated in our hypothesis, we had expected to see a relationship between femur abduction level and joint reaction forces/moments – that is to say, we expected more abduction to lead to greater internal forces and moments in the lumbopelvic joint. However, the simulations showed that it may not be the amount of abduction that was important, but just the fact that there was any abduction away from a neutral position. Meaning, it may not be enough to get the residual limb close to anatomical alignment, it needs to be fully aligned to relieve stresses on the lumbopelvic joint.

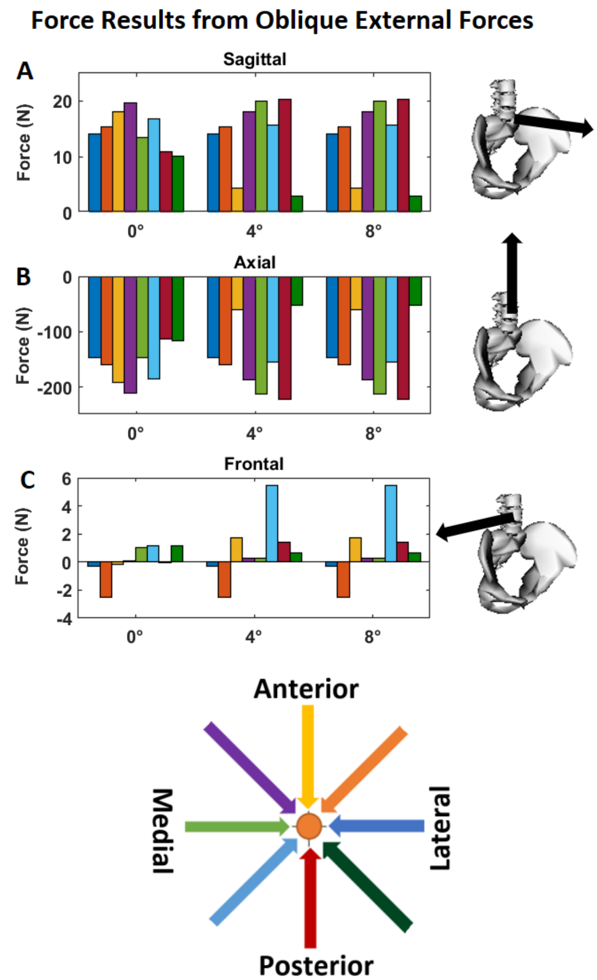

Figure 2: Data from joint reaction analysis showing a change in the force profile from aligned limb to abducted limb. The different colors represent directions of applied force on residual limb. Results shown are reactions to 10N oblique external forces. The arrows emanating from the pelvis at the right indicate positive sign convention for each force.

D. Future Work

In this study, we chose to simplify the lower spine to one lumbopelvic joint and to not represent the sacroiliac joint. However, there is still much that can be learned from adding more layers of complexity into the model. This could be through modeling each of the vertebral joints in the lumbar or releasing the hip joints and tracking how their compensations affect the lumbopelvic joint.

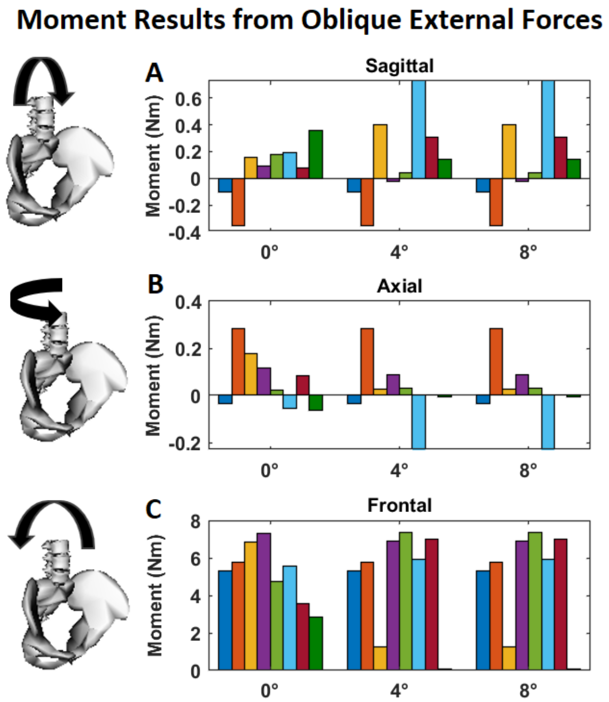

Figure 3: Data from joint reaction analysis showing a change in the moment profile from aligned limb to abducted limb. The different colors represent directions of applied force on residual limb (see Fig. 2). Results shown are reactions to 10N oblique external forces. The arrows emanating from the pelvis at the left indicate positive sign convention for the moments.

V. Conclusion

While there was not a change in the profile of lumbopelvic joint reaction forces and moments for changes in femur abduction level in response to a transverse external force, there is a change in profile in response to an oblique external force. This is important because an oblique external force mimics the effects of walking and ambulation on multiple types of surfaces that individuals with limb loss would encounter during daily life. Moreover, the fact that the change in joint reaction forces and moments happens from alignment to non-alignment and does not appear to grow with further non-alignment, underscores the value of amputation procedures that prioritize realigning the residual limb to a neutral limb posture. There are indications that these more extensive initial surgical (or limb revision) procedures may have a substantial effect on maintaining normal mechanical loading in the lower back, and possibly limit chronic pain, in individuals with transfemoral amputation.

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