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The influence of limb alignment and transfemoral amputation technique on muscle capacity during gait

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ABSTRACT
Many factors influence successful outcomes following transfemoral amputation. One factor is surgical technique. In this study, the influence of limb alignment and surgical technique on a muscle's capacity to generate force was examined using musculoskeletal modeling. Non-amputee and transfemoral amputee models were analyzed while hip adduction, femur length, and reattached muscle wrap position, tension and stabilization technique were systematically varied. With muscle tension preserved, wrap position and femur length had little influence on muscle capacity. However, limb alignment, muscle tension and stabilization technique notably influenced muscle capacity. Overall, myodesis stabilization provided greater muscle balance and function than myoplasty stabilization.

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Amputee; myodesis; myoplasty; surgery; musculoskeletal modeling; biomechanics

Introduction

Recent estimates indicate there are over 1.7 million people living with amputation in the United States, with approximately 54% due to dysvascular disease, 45% due to trauma and less than 2% due to cancer (Ziegler-Graham et al. 2008). The prevalence of amputation is increasing and it is projected to reach 3.6 million people by 2050 (Ziegler-Graham et al. 2008). In addition to individuals in the general population, recent conflicts have resulted in a cohort of young active individuals with traumatic amputation (Krueger et al. 2012). For these individuals, restoring a high-level of mobility and functionality post-amputation is a primary goal when determining the optimal surgical technique and rehabilitation strategy. Previous work has examined the influence of residual limb length on gait performance in transfemoral amputees and found that amputees with longer residual limbs exhibit less excursion in their torso (Bell et al. 2013) and pelvis (Baum et al. 2008; Goujon-Pillet et al. 2008; Bell et al. 2013) and walk at faster self-selected speeds (Bell et al. 2013), but do not have lower energy expenditure (Bell et al. 2014). However, little research has been done to examine the influence of specific transfemoral amputation surgical techniques on the capacity of individual muscles to generate force and moments about the hip to maintain proper muscle balance and limb alignment during gait.

Important aspects of the surgical technique include the femur length, which muscles are reattached to the residual limb, the wrap position of the reattached muscles, and the tension and stabilization method used in the reattachment. These factors are critical in maintaining a muscle-balanced and aligned residual limb during gait (e.g. Gottschalk 2004). In transfemoral amputations, essential muscles to reattach include the adductor magnus to maintain hip adductor-abductor balance, the rectus femoris to maintain hip flexor-extensor balance and the hamstrings to provide hip flexor-extensor and adductor-abductor balance (e.g. Gottschalk 2004; Tintle et al. 2010). Often smaller muscles (e.g. gracilis and sartorius) are left unattached to minimize suturing and surgery time.

Traditional muscle stabilization using myoplasty involves suturing agonist and antagonist muscles together over the residual end of the femur. However, this primarily provides distal end coverage and does not preserve muscle tension (Gottschalk 2004). For this reason, some have recommended the use of myodesis stabilization for the adductor magnus (e.g. Gottschalk 2004; Tintle et al. 2010) and medial hamstrings (e.g. Tintle et al. 2010), in which muscles are reattached directly to the femur under tension. Myodesis is a longer surgical procedure than the more traditional myoplasty, and thus evidence demonstrating that this technique improves the capacity of

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individual muscles to generate force and moments about the hip is needed to justify the increased cost and risk associated with the increased surgery time.

The influence of specific surgical techniques (e.g. reattachment tension) on muscle capacity has not been systematically examined *in vivo* due to the highly invasive nature of the procedure. However, musculoskeletal modeling is a powerful non-invasive framework through which to explore different surgical techniques, and it has been used previously to investigate the influence of surgical interventions such as tendon transfer (e.g. Delp et al. 1994; Magermans et al. 2004), joint replacement (Piazza and Delp 2001) and paraspinal muscle resection (Bresnahan et al. 2010). In addition, musculoskeletal modeling and simulation has been used to provide insight into key clinical questions such as the individual muscle contributions to walking mechanics (e.g. Anderson and Pandy 2003; Neptune et al. 2004; Liu et al. 2006; McGowan et al. 2009), the influence of walking speed on muscle function (e.g. Arnold et al. 2007; Liu et al. 2008; Neptune et al. 2008), and the influence of assistive device design, such as prosthetic foot stiffness (Fey et al. 2012) and wheelchair seat position (Slowik and Neptune 2013), on metabolic cost. Thus, musculoskeletal modeling is an ideal framework to identify the optimal surgical techniques to maintain a muscle-balanced and aligned residual limb prior to clinical trials.

Therefore, the overall goal of this study was to systematically investigate the influence of residual limb alignment and transfemoral amputation technique (i.e. wrap position, femur length, muscle tension and stabilization) on the capacity of individual muscles to generate force and moments about the hip to maintain proper muscle balance during gait using advanced musculoskeletal modeling techniques. An improved understanding of how surgical technique affects muscle capacity can be used to guide the selection of specific techniques when considering factors such as surgical cost and risk. Further, those muscle groups found to be critical for maintaining muscle balance can be identified and targeted in therapies to ensure optimal functionality and improve rehabilitation outcomes.

Methods

To investigate the influence of limb alignment and surgical technique on muscle capacity, we systematically varied hip adduction angle, femur length, wrap position, muscle tension, and stabilization technique using a musculoskeletal modeling framework. Hip adduction angle was varied from −20° to 10° relative to healthy gait kinematics, femur resection was varied from 10 to 14 cm, wrap position was varied from a medial insertion to an anterior insertion, muscle tension was varied relative to that of an intact muscle (80–100% of intact neutral tension) and stabilization techniques of myoplasty versus myodesis were compared.

Non-amputee model

A non-amputee subject was modeled using a well-established lower extremity musculoskeletal model in OpenSim 3.1 (Delp et al. 2007). The model had 23 degrees of freedom and 92 musculotendon actuators representing 76 major muscles in the lower extremities and torso. The musculotendon model used was based on the work of Thelen (2003). Musculotendon parameters were derived from Delp et al. (1990), and optimal fiber lengths and pennation angles were taken from Wickiewicz et al. (1983) and Friederich and Brand (1990). Twelve body segments were used to represent the torso, pelvis, and bilateral femur, tibia, calcaneus, talus and toes. The inertial properties of the body segments were derived from Anderson and Pandy (1999), and joint definitions were derived from Delp et al. (1990). Experimentally-collected three-dimensional kinematics and kinetics of a healthy control subject performing overground walking at a controlled speed based on leg length were used to perform inverse kinematics (Wilken et al. 2012). A residual reduction algorithm (RRA) was used to ensure dynamic consistency of the experimental kinematics and ground reaction forces, and computed muscle control (CMC) was performed to generate a set of muscle activations that, when the experimental ground reaction forces were applied, reproduced the experimental kinematics (Thelen and Anderson 2006).

Amputee model

The musculoskeletal model was then modified to represent a transfemoral amputee. The lower-leg body segments (tibia, talus and foot) were removed from the residual limb, along with ankle and uniarticular knee muscles. A prosthesis was not modeled as the following analyses did not necessitate its inclusion.

To investigate the influence of specific surgical techniques, muscles that are normally considered for reattachment during transfemoral amputation (i.e. adductor magnus, rectus femoris, biceps femoris long head, semimembranosus, semitendinosus, gracilis, sartorius and tensor fasciae latae) had their muscle geometry and properties systematically altered to represent the different surgical techniques. Muscle geometry was modified by adjusting the attachment points to the femur and adding cylindrical wrapping surfaces to emulate muscle wrapping over the residual end of the bone. Muscle parameters, specifically the tendon slack length (TSL), were modified to alter the muscle tension relative to that normally found in an intact muscle with the limb in a neutral position. This approach was used to replicate efforts to restore tension prior to reattachment. The resting length of the musculotendon unit is the sum of the optimal fiber length and TSL. Decreasing TSL in the model is analogous to leaving a shorter muscle segment. Therefore, when the musculotendon unit is stretched to maintain its total length, muscle tension is increased. Conversely, increasing the TSL acts to lengthen the musculotendon unit, thus decreasing muscle tension. By altering TSL in the model, specific percentages of intact neutral tension can be preserved in a zero activation state (i.e. emulating the state of the relaxed muscle during surgery). In a myoplasty stabilization, muscle tension is not preserved, and thus stabilization by myoplasty was modeled by maintaining the intact TSL, and not the neutral muscle tension. In a myodesis stabilization, muscle tension is preserved as the muscle is anchored directly to bone, and thus stabilization by myodesis was modeled by preserving 100% of the intact neutral tension in a zero activation state.

A series of amputee models (Table 1) were generated to examine the influence of hip adduction, femur length, muscle wrap position, muscle tension and stabilization technique on the capacity of individual muscles to generate force and moments about the hip. Specifically, we quantified differences in hip adduction moment arm and contribution to the frontal plane hip moment. Analyses were performed using healthy gait kinematics and three different states of muscle activation for all muscles: zero activation, normal activation as determined by CMC, and full activation.

The influence of hip adduction position on muscle capacity was investigated by shifting the healthy gait kinematics by −20°, −10°, 0° and 10° of hip adduction. The resulting muscle capacity was then assessed at mid-stance.

The influence of femur length was investigated by comparing the muscle capacity in amputee models with 10, 12 and 14 cm of femur resected at the points of initial contact, mid-stance and mid-swing. The resection lengths investigated represent the largest range in which myodesis stabilization could be performed. Muscle reattachments, relative reattachment locations and stabilization techniques were modeled consistently across femur lengths.

The influence of the adductor magnus wrap position on muscle capacity was examined by comparing four different amputee models (12 cm femur resection) with varying wrap positions. The muscle wrap positions modeled were a medial, non-wrapped insertion (Figure 1(a)), a lateral insertion (Figure 1(b)), an anterior-lateral insertion (Figure 1(c)) and an anterior insertion (Figure 1(d)). The resulting muscle capacity was assessed at initial contact, mid-stance and mid-swing.

To investigate the influence of muscle tension, a comparison of muscle capacity at initial contact, mid-stance and mid-swing was performed on amputee models (12 cm femur resection) with 80, 90 and 100% of the intact neutral tension preserved.

A comparison of muscle stabilization technique (i.e. myodesis vs. myoplasty) was performed by computing the net hip joint frontal plane moment in the amputee models (12 cm femur resection) with either myodesis or myoplasty of the adductor magnus and semimembranosus. Joint moments of the non-amputee model, the myoplasty stabilization model, and the myodesis stabilization model were compared at initial contact, mid-stance and mid-swing.

Table 1. Hip alignment and transfemoral amputation surgical parameters analyzed in this study.

Parameter	Values
Hip alignment	20° abduction 10° abduction 0° neutral 10° adduction
Femur resection	Non-amputee 10 cm 12 cm 14 cm
Wrap position (adductor magnus)	Medial insertion Lateral insertion Anterior-lateral insertion Anterior insertion
Reattachment tension	80% NTC 90% NTC 100% NTC
Muscle stabilization (adductor magnus and semimembranosus)	Non-amputee Myodesis Myoplasty

Notes: For each parameter, the corresponding values compared in this study are provided. Reattachment tension values are provided as the percent of neutral tension conserved (NTC).

Results

The total frontal plane hip moment and gluteus medius contribution to the hip moment during mid-stance changed with variations in hip adduction angle (Figure 2). In all muscle activation states (zero, normal and full), the net frontal plane hip abduction moment was smallest (or even became an adduction moment) when the femur was most abducted (i.e. −20° shift). Gluteus medius contribution to the hip abduction moment during mid-stance was affected by femur adduction angle. Under normal and full muscle activation, the gluteus medius contribution to the hip abduction moment was largest in the neutral position (i.e. 0° shift).

The frontal plane hip moment contributions from different muscles varied across femur lengths (Figure 3). Muscles that were candidates for reattachment and modeled with myodesis stabilization (adductor magnus and semimembranosus) remained similar across femur

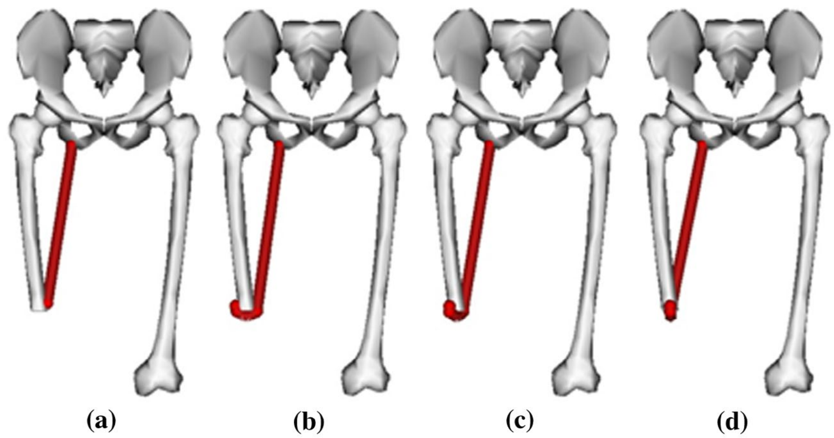

Figure 1. Adductor magnus wrap position. Wrap positions modeled in this study were: (a) medial insertion, (b) lateral insertion, (c) anterior-lateral insertion, and (d) anterior insertion.

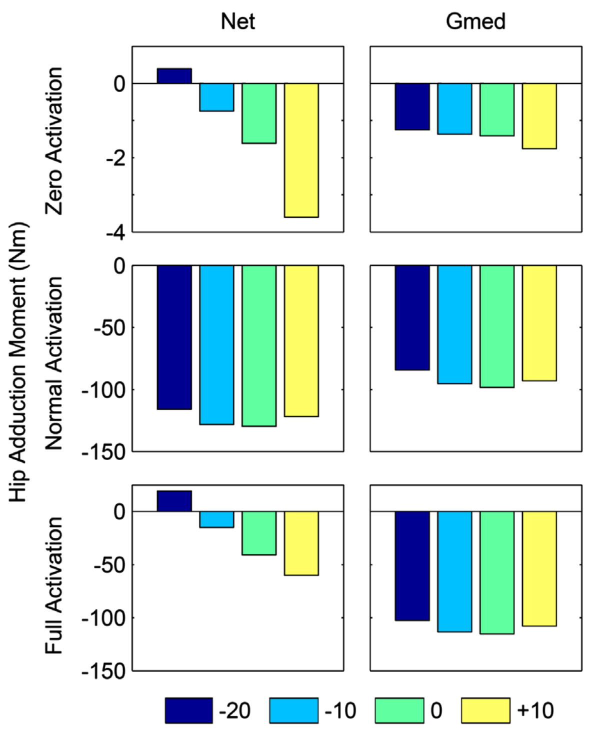

Figure 2. Net frontal plane hip moment (positive is adduction, negative is abduction) and gluteus medius (Gmed) contribution to the frontal plane hip moment (Nm) at mid-stance for zero, normal and full activation. Results are shown for kinematics containing a −20°, −10°, 0° and +10° shift from normal hip adduction.
Note: The scale is different for the zero activation state.

resections. At both 12 and 14 cm resections, biceps femoris long head no longer contributed to the frontal plane hip moment for all activation levels. At 10 and 12 cm resections, tensor fasciae latae contributed less than 10% of its intact moment for zero activation, and at a 14 cm resection it contributed less than 10% of its intact moment for all activation levels.

Adductor magnus wrap position did not meaningfully alter the hip adduction moment arm at any of the three points in the gait cycle examined (Figure 4). The largest difference in moment arm was observed during mid-stance where the anterior insertion produces a moment arm that is 3.3 mm greater than that of the lateral insertion (8.9% difference).

Muscle tension significantly influenced muscle capacity. Higher percentages of preserved tension resulted in larger fiber forces, thus resulting in a larger contribution (positive or negative) to the net frontal plane hip moment (Figure 5). For all activation levels, the net hip adduction moment in the amputee model was larger with myodesis stabilization (Figure 6).

Discussion

The goal of this study was to examine the influence of limb alignment and transfemoral amputation technique on the capacity of individual muscles to generate force and moments about the hip. A greater capacity to generate forces and moments indicates an improved ability to maintain proper muscle balance during gait. Through understanding which surgical techniques are critical to maintaining muscle capacity, and conversely those that have minimal effect, surgeons can streamline amputation procedures to maximize muscle capacity, minimize surgical cost and risk and improve rehabilitation outcomes.

The changes in muscle capacity associated with changes in hip alignment (Figure 2) highlight the importance of maintaining proper residual limb alignment during gait. If a limb is not well aligned and tends to abduct, there can be an increase in gait asymmetries resulting in inefficient gait patterns (e.g. Gottschalk 1999). Thus, it is critical that surgical techniques (e.g. wrap position, tension preserved and femur length) maintain the dynamic balance of the residual limb to allow efficient and functional gait.

Residual limb length is often determined by the nature of the injury or condition requiring amputation. However, if there is flexibility, the surgeon must decide

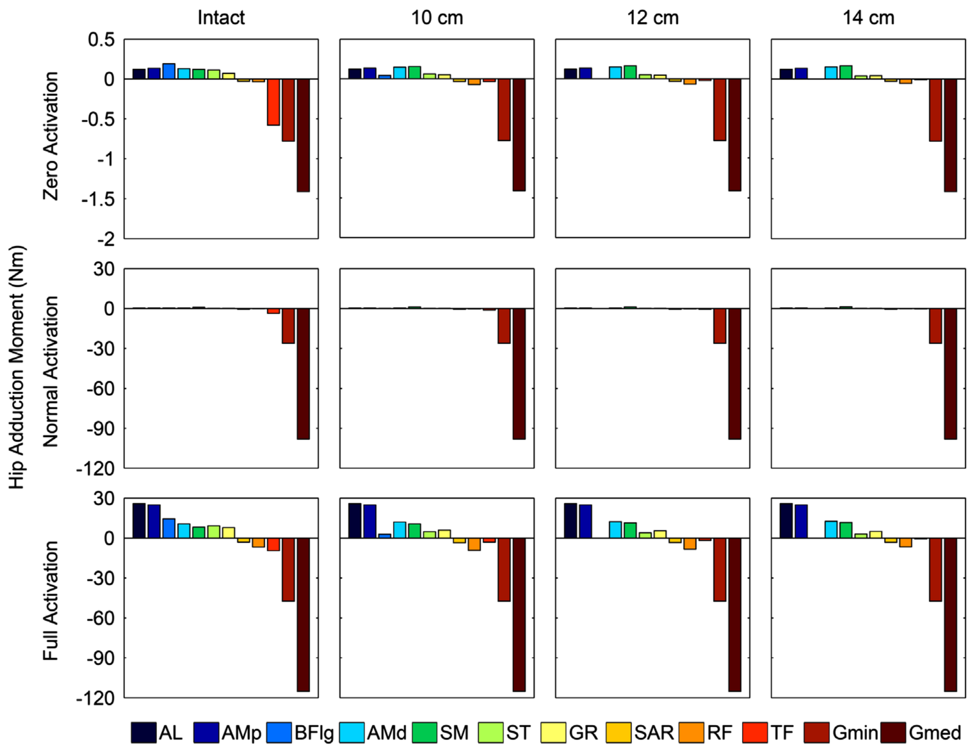

Figure 3. Frontal plane hip moment (Nm) contributions at mid-stance across activation level and length of femur resection. Positive frontal plane hip moment indicates adduction, negative indicates abduction. Hip moments are presented for large positive and negative contributors to the net hip moment, as well as for the reattachment candidates in the amputation procedure: adductor longus (AL), proximal adductor magnus (AMp), biceps femoris long head (BFlg), distal adductor magnus (AMd), semimembranosus (SM), semitendinosus (ST), gracilis (GR), sartorius (SAR), rectus femoris (RF), tensor fasciae latae (TF), gluteus minimus (Gmin) and gluteus medius (Gmed). Moments are presented for a non-amputee model (Intact) as well as 10, 12 and 14 cm resections across three levels of muscle activation (zero, normal and full activation).
Note: The scale differs for the zero activation state.

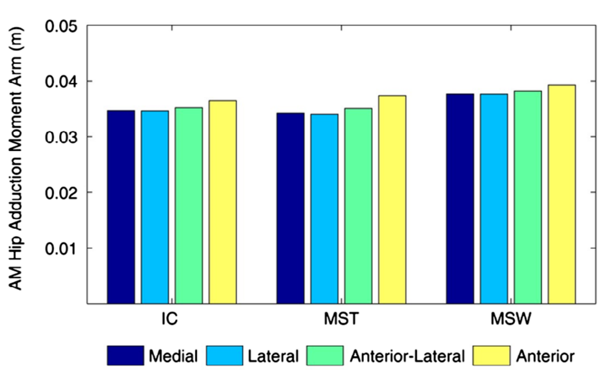

Figure 4. The influence of wrap position on adductor magnus (AM) hip adduction moment arm (m). Moment arms are shown at three different points in the gait cycle (initial contact (IC), mid-stance (MST), and mid-swing (MSW)), for four different wrap configurations: medial insertion, lateral insertion, anterior-lateral insertion and anterior insertion.

the femur resection length. Previously, length preservation has been advocated (e.g. Gottschalk 1999) as being important for positive functional outcomes, and studies have shown that residual femur length does influence self-selected walking speeds (Bell et al. 2013) and gait kinematics (Baum et al. 2008; Goujon-Pillet et al. 2008; Bell et al. 2013). The results of the present study indicate that a shorter residual limb may decrease frontal plane hip moment contribution of reattached muscles. However, this effect was not observed in muscles with myodesis stabilization, thus suggesting that muscle capacity can be preserved in shorter residual limbs by preserving neutral tension during reattachment. However, preserving tension in shorter residual limbs can be challenging when the tendinous portion of the adductor magnus is missing, which makes it difficult to sufficiently stretch and attach the muscle. Thus, the present study only analyzed residual limb lengths that could utilize adductor tendon attachments and did not investigate shorter residual limbs which may have important implications for other factors such as socket fit.

Changes in adductor magnus wrap position resulted in only minor changes in hip adduction moment arm (Figure 3), indicating that this is not a critical surgical parameter. Some authors (e.g. Gottschalk 2004; Tintle et al. 2010) suggest a lateral attachment of the adductor myodesis, although this is likely due to the anatomical position of the

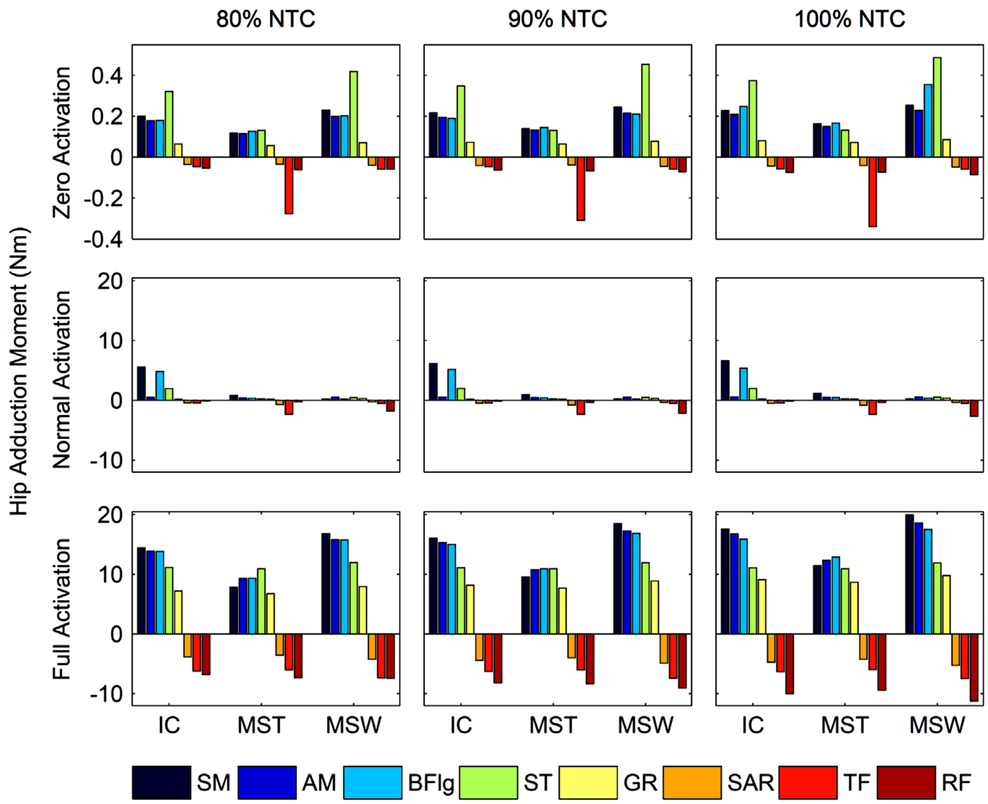

Figure 5. The influence of muscle reattachment tension on muscle contribution to the frontal plane hip moment. Hip moments (Nm) are shown at three different points in the gait cycle: initial contact (IC), mid-stance (MST), and mid-swing (MSW) for reattachment candidates at three different percentages of intact neutral tension preserved (80, 90, and 100%) and across three levels of muscle activation (zero, normal and full activation). Positive frontal plane hip moment indicates adduction, negative indicates abduction. Reattachment candidates are semimembranosus (SM), distal adductor magnus (AM), biceps femoris long head (BFlg), semitendinosus (ST), gracilis (GR), sartorius (SAR), tensor fasciae latae (TF) and rectus femoris (RF).
Note: The scale differs for the zero activation state.

adductor magnus with respect to the femur, which facilitates this particular wrap position. However, the present study suggests that wrap position should be selected that is most appropriate based on the available tissue (e.g. the wrap position that ensures preservation of muscle tension and a stable fixation). Thus, as muscle capacity in a medial attachment does not largely differ from a lateral attachment when tension is preserved, surgeons may have the option of leaving a longer residual limb, as a lateral attachment may require additional resection, which has important implications for socket fit and within-socket limb stabilization.

Although this study revealed that wrap position is not critical, muscle reattachment tension was found to greatly influence the muscle's capacity to generate force. Increased initial tension results in greater muscle fiber forces and thus larger frontal plane hip moment generating capacity. Previous studies have recommended the use of myodesis stabilization for the adductor magnus and medial hamstrings (e.g. Tintle et al. 2010), which is consistent with the present study that highlights the importance of maintaining muscle tension. Reattaching muscles under tension allows for greater capacity to generate forces and moments, and thus could potentially provide greater limb functionality post-surgery.

Finally, we examined the difference in muscle balance between a non-amputee model, an amputee model in which the adductor magnus and semimembranosus were reattached using a myoplasty stabilization, and an amputee model in which they were reattached using a myodesis stabilization. The net hip adduction moments observed in these models indicate that myodesis stabilization may result in a larger hip adduction moment than myoplasty stabilization, and thus may produce a more favorable muscle balance. These findings, along with the reattachment tension sensitivity results support the use of myodesis stabilization on both the adductor magnus and medial hamstrings (e.g. Tintle et al. 2010).

One potential limitation of this study is that kinematics of only one subject were represented. However, we performed similar analyses using additional kinematic data, including from younger and older subjects, which yielded similar findings. This highlights the robustness of these results to inter-subject differences in gait patterns. In addition, the subject kinematics were from a non-amputee subject, although differences between amputee

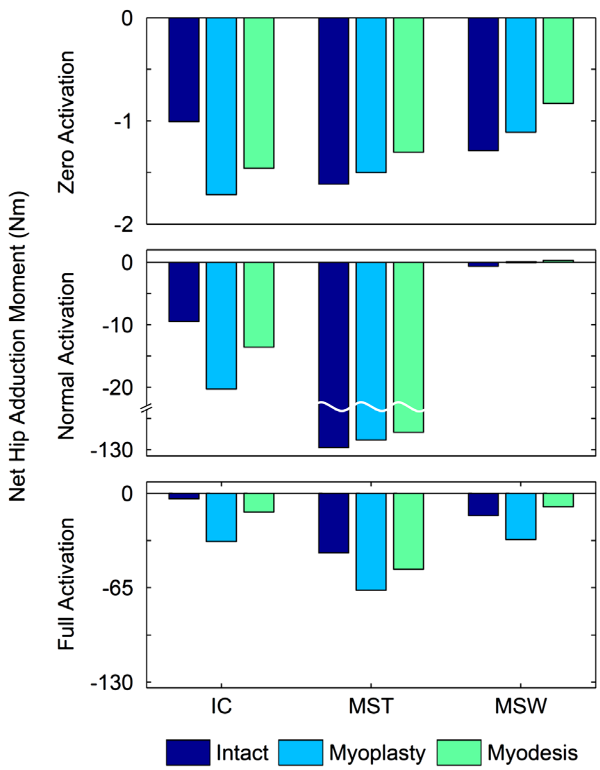

Figure 6. The net frontal plane hip moment (Nm) at initial contact (IC), mid-stance (MST) and mid-swing (MSW) of a non-amputee model (Intact), an amputee model with myoplasty stabilization, and an amputee model with myodesis stabilization of the adductor magnus and semimembranosus. Moments were compared across three levels of muscle activation (zero, normal and full activation). Positive frontal plane moment indicates hip adduction, negative indicates hip abduction.
Note: The scales differ across the three rows of figures.

and able-bodied gait have previously been shown (e.g. Jaegers et al. 1995), and more recently, the differences between transfemoral amputee and non-amputee muscle activity during walking have been observed (Wentink et al. 2013). However, while kinematic differences are often present in amputee gait, performing this study using healthy kinematics allowed for a direct comparison between non-amputee and amputee models. Future analyses should include forward dynamic simulations of amputee models tracking transfemoral amputee data to further assess the efficacy of different surgical techniques on dynamic muscle capacity and function.

Another potential limitation of this study is that it does not account for changes that may occur in the residual limb post-surgery. However, reattached and functioning muscles may be less susceptible to atrophy and remodeling, and could potentially play a positive role in stabilizing the limb within the socket. In addition, this study did not consider other post-surgery factors such as muscle pull out strength or tissue healing. While changes may occur in the residual limb over time, the current findings highlight the surgical techniques critical to maintaining muscle capacity post-surgery, as well as potential targets for rehabilitation therapies.

Conclusion

In summary, muscle wrap orientation had little effect on muscle capacity. Similarly, if muscle tension is preserved, femur length had little effect. In contrast, limb alignment was found to influence the ability of muscles to generate forces and moments about the hip joint. Muscle reattachment tension had the greatest influence on muscle capacity, with increases in tension resulting in higher fiber forces and contributions to the hip adduction moment. Thus, myodesis stabilization, which allows for greater muscle tension, may provide superior hip muscle balance and function compared to myoplasty stabilization or when leaving muscles unattached.

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Disclosure statement

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