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Effect of Muscle Loss on Hip Muscular Effort during the Swing Phase of Transfemoral Amputee Gait: A Simulation Study

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***Abstract*—**The effect of muscle loss due to transfemoral amputation, on energy expenditure of hip joint and individual residual muscles was simulated. During swing phase of gait, with each muscle as an ideal force generator, the lower extremity was modeled as a two-degree of freedom linkage, for which hip and knee were joints. According to results, muscle loss will not lead to higher energy expenditure of hip joint, as long as other parameters of limb remain unaffected. This finding maybe due to the role of biarticular muscles in hip and knee joints motion. Moreover, if hip flexors are removed from the residual limb, residual flexors, and if hip extensors are removed, residual extensors will do more work. In line with the common practice in transfemoral amputation, this result demonstrates during transfemoral amputation, it is important to maintain the length of residual limb as much as possible.

***Keywords*—**Amputation Level, Simulation, Transfemoral Amputee.

I. INTRODUCTION

THE activities of muscles, which are responsible for movement at joints [1], determine gait efficiency [2]. To investigate the role played by muscles during gait, numerous research activities have been conducted. For example, Piazza and Delp [3] examined the roles of muscles in determining swing phase knee flexion. Jonkers et al. [4] analyzed the function of individual muscles during the single stance and swing phases of gait, using muscle driven forward simulation. Arnold et al. [5] analyzed a series of three-dimensional, muscle driven dynamic simulations to quantify the angular accelerations of the knee induced by muscles and other factors during swing. Besier et al. [6] used an EMG-driven musculoskeletal model of the knee to estimate quadriceps forces during walking and running.

Due to the importance of the functionality of muscles during gait, when a surgeon performs a transfemoral amputation, it is important to maintain the length of a residual limb as much as possible [7]. Yet, since some of the muscles are lost, the gait efficiency of an amputee differs from that of a healthy subject. According to the experimental records of energy expenditure, as the level of amputation lowers, gait efficiency improves. Traugh et al. [8] reported that energy expenditure of ambulation in patients with transfemoral amputation is more than that of normal persons. Waters et al. [9] reported that the lower the level of amputation is, the better amputee walking performance will be. Huang et al. [10] reported that mean oxygen consumption of transtibial amputees is lower than that of transfemoral amputees, and higher than that of unimpaired subjects. Pinzur et al. [11] found that oxygen consumption per meter walk increased with more proximal amputation. Boonstra et al. [12] reported that energy expenditure of the amputee during ambulation was higher than that of non-amputee and also, residual limb length affects energy expenditure. Hunter et al. [13] found that energy expenditure of transtibial amputees is higher than that of able-bodied during harness-supported treadmill ambulation. According to Genin et al. [14], the minimum cost of walking with different speeds increased with the level of amputation.

Aforementioned empirical studies ([8]- [14]), are not capable of exploring the effects of specific parameters on gait. During gait parameters like muscles, mass and moment of inertia of limbs, and the initial conditions affect motion. Empirical studies will reveal the effects that all of these parameters will have, but they are not capable of investigating the role of muscle loss. Specifically, they are not able to quantify the contribution of individual muscles. While recording electromyography (EMG) signals can show the activities of superficial muscles [15], it cannot quantify the role of individual muscles. Inverse dynamics solution that models the overall effects of muscles at joints, is another method that have been used to calculate the contribution of muscles during gait (for example, [16] and [17]). However, studies based on this method cannot quantify the function of individual muscles, for in the equations of motion they take the role of muscles into account, by including their overall torque about hip and knee joints. Considering the limitations of prior studies, this study was carried out to explore the

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Open Science Index, Biomedical and Biological Engineering Vol:4, No:1, 2010 publications.waset.org/12941.pdf

contribution of lower limb individual muscles to a transfemoral amputee swing phase of gait. In this context, this paper aims to answer the following questions: does the hip joint of the transected leg contribute to the increased energy expenditure of the gait of a transfemoral amputee, during swing phase of gait? In the residual limb of an amputee, what is the effect of muscle loss on the work done by the individual muscles of residual limb?

Moreover, the simulation presented in this paper can help to investigate the effects of different prosthetic leg components on the gait of amputees. While this investigation can be carried out experimentally ([18]- [22]), simulation provides a much less expensive and more convenient tool [23]. With a general approach similar to the previous simulations of swing phase, for example, Piazza and Delp [3] and Jonkers et al. [4], this paper investigates the contribution of individual muscles during the swing phase of transfemoral amputee gait.

II. Materials and Methods

A. Musculoskeletal Model

The musculoskeletal actuators of lower extremity of the intact limb, and transfemoral one were modeled. The attachment coordinates of all muscles in the reference skeletal frames were based on the data reported by Delp [24]. In the transfemoral models, assuming a myodesis, in which the new attachment of muscle end is fixed to the amputated tip of the bone, the distal attachment of the transected muscles was changed ([7] and [25]). The muscles included in the intact model were: 1- iliacus, 2- psoaa, 3- superior component of gluteus maximus (GMAX1), 4- middle component of gluteus maximus (GMAX2), 5- inferior component of gluteus maximus (GMAX3), 6- rectus femoris (RF), 7- adductor longus (ADDLONG), 8- semimembranosus (SEMIMEM) 9- semitendinosus (SEMITEN), 10- long head of biceps femoris (BIFEMLH), 11- short head of biceps femoris (BIFEMSH), 12- vastus medialis (VASMED), 13- vastus intermedius (VASINT), 14- vastus lateralis (VASLAT), 15- medial head of gastrocnemius, 16- lateral head of gastrocnemius. To assess the effect of muscle loss, three models of a transfemoral limb were analyzed which are summarized in Table I.

The equations of motion are taken from Piazza and Delp [3]:

$$\begin{bmatrix}\ddot{\theta}_H \\ -\ddot{\theta}_K\end{bmatrix} = M^{-1}C\begin{bmatrix}\dot{\theta}_H^2 \\ \dot{\theta}_K^2\end{bmatrix} + M^{-1}V\begin{bmatrix}-\dot{\theta}_H\dot{\theta}_K \\ 0.0\end{bmatrix} + M^{-1}P\begin{bmatrix}\ddot{x} \\ \ddot{y}\end{bmatrix} + M^{-1}G + M^{-1}\begin{bmatrix}M_H \\ -M_K\end{bmatrix} \quad (1)$$

where $\ddot{\theta}_H$ and $\ddot{\theta}_K$ are hip and shank rotational accelerations which are determined from experimental data, $\ddot{x}$ and $\ddot{y}$ are the acceleration of hip joint in horizontal and vertical directions, respectively. M, C, V, P and G depend upon joint angles and inertial parameters. For details of these parameters, see the report by Piazza and Delp [3]. M_H is the torque resulted from muscle forces about hip joint, and M_K is the torque about knee joint. For the intact limb, this torque is resulted from muscle forces and for the transfemoral limb it is resulted from prosthetic knee. In the swing phase of a transfemoral amputee, the prosthetic knee controls the motion in the knee joint. To take the torque of a prosthetic knee into account a pair of antagonistic muscles is included in the knee joint. In other words, to model the torque produced by a prosthetic knee, a pair of virtual muscles that span the knee joint is embedded. This approach is based on the study reported by Hale [17].

Since the use of dynamic optimization rather than static optimization is not justified if one seeks only to estimate muscle forces [26], the static optimization solution is used. In addition, as taking muscle force-length-velocity properties into account produces results similar to results when they are excluded, each muscle has been treated as an ideal force generator [26]. The performance criterion was chosen as the sum of the squared muscle activations [26]:

$$J = \sum_{m=1}^{MN} (a_m)^2 \quad (2)$$

where J is the performance criterion, MN is the number of muscles, and a_m is the activation of each muscle.

For muscles to control the motion of hip and knee joints, the equality constraint (3) was enforced:

$$\begin{bmatrix}\ddot{\theta}_H \\ \ddot{\theta}_K\end{bmatrix} - \begin{bmatrix}(\ddot{\theta}_H)_{\text{exp.}} \\ (\ddot{\theta}_K)_{\text{exp.}}\end{bmatrix} = 0.0 \quad (3)$$

TABLE I
MUSCLES OF DIFFERENT MODELS OF LOWER EXTREMITY.

Model	Muscles preserved	Muscles transected	Muscles removed
Intact Limb 1	1 to 16	-	-
Intact Limb 2	1 to 16	-	-
Transfemoral limb 1	1, 2, 3, 4, 5, 7	6, 8, 9, 10	11, 12, 13, 14, 15, 16
Transfemoral limb 2	1, 2, 3, 4, 5, 7	6	8, 9, 10, 11, 12, 13, 14, 15, 16
Transfemoral limb 3	1, 2, 3, 4, 5, 7	-	6, 8, 9, 10, 11, 12, 13, 14, 15, 16
Transfemoral limb 4	1, 2, 3, 4, 5	-	6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16

Open Science Index, Biomedical and Biological Engineering Vol:4, No:1, 2010 publications.waset.org/12941.pdf

where $(\ddot{\theta}_H)_{\text{exp.}}$,and $(\ddot{\theta}_K)_{\text{exp.}}$ are experimental acceleration of hip and knee joints, respectively. The experimental accelerations in (3) are computed by twice differentiation of experimental knee and hip joint angles. In addition, the values of muscles' activations are bounded between 0 and 1.0.

B. Experimental Data

The hip and knee angles during the swing phase have been used from an experiment in which a transfemoral amputee was asked to walk along a walkway at his natural cadence. He was 45 years old, 165 cm high, with 85kg weight, and had more than 12 months experience in using a transfemoral prosthesis with Endolite esprit foot (Chas. A. Blatchford and Sons Ltd, Basingstoke, UK) and a Naptesco Hybrid knee (Naptesco Corp., Japan). Kinematic data of the lower limb during walking were measured by a motion analysis system (WINanalyze 1.4, 3D, Mikromak Gmbh, 1998, Germany). A high speed camera (Kodak Motion Corder, SR- 1000, Dynamic Analysis System Pte Ltd, Singapore) was used to record the two-dimensional motion of the body segments taken at 125 frames s^{-1}. As shown in Fig. 1, three reflective markers were attached to ankle (lateral malleolus), knee (lateral femoral epicondyle) and hip (greater trochanter). The subject velocity was almost 50 steps/min.

Fig. 1 The locations of markers used in the gait analysis experiment.

Two intact models were analyzed. In the first one, the intact limb hip and knee angles measured by gait analysis system were inputs for the model. Also, mass and moment of inertia pertain to data calculated for the this limb. In the second intact model, all the parameters of the intact model are the same as transected leg. As will be explained in "Discussion", this model is analyzed to assess the role of muscle loss in hip joint kinetics.

The values for hip and knee initial velocity and angle were calculated from experimental records. The swing phase which was from a leg toe-off to heel strike was almost 0.42 seconds. Similar to previous studies (for example [3] and [25]) it is assumed that the mass of thigh and shank are located at their center of mass.

Using a backward difference scheme, (1) was solved numerically in MATLAB programming language. Using 100 time steps, on a laptop model Intel® Core™ 2 Duo CPU T7250 @ 2.00 GHz with 3070 MB RAM, it took about 60 minutes for the intact model to run. The execution time for each transfemoral model was approximately 45 minutes.

III. RESULTS

To validate the accuracy of simulation, the torque of hip and knee joints calculated in this study and those reported by Winter [27], who used an inverse dynamics simulation to calculate muscular joint torques from measured joint kinematics, are compared in Figs. 2 and 3.

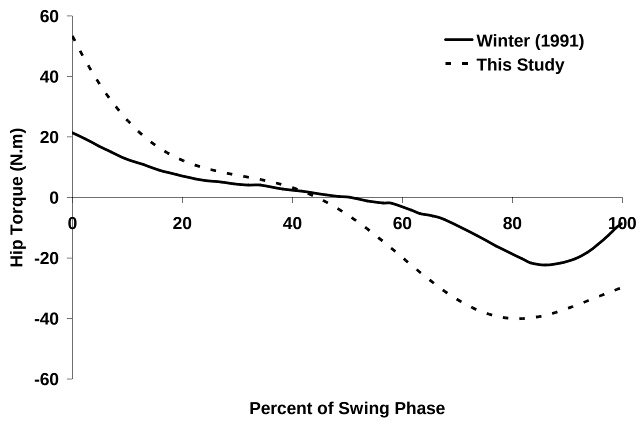

Fig. 2 Comparison between calculated hip torque with that reported by Winter [27].

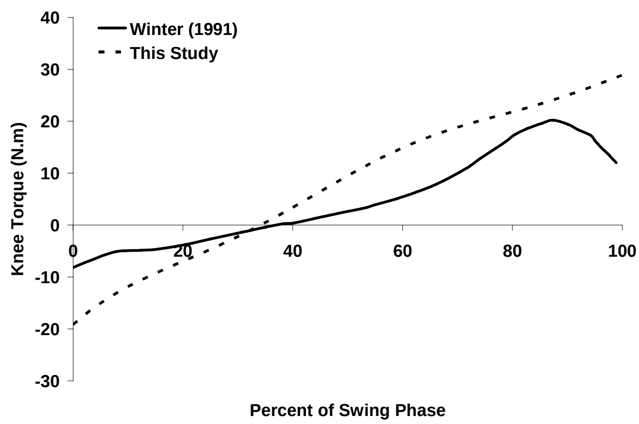

Fig. 3 Comparison between calculated knee torque with that reported by Winter [27].

Since for this study, we sought to assess the effects of muscle loss on energy expenditure of hip joint and individual muscles of residual limb, in Table II their total work for all models is shown.

TABLE II
TOTAL WORK DONE BY THE HIP JOINT AND INDIVIDUAL MUSCLES FOR DIFFERENT MODELS (J).

Model	Intact 1	Intact 2	Transfemoral 1	Transfemoral 2	Transfemoral 3	Transfemoral 4
Hip	8.522	5.432	5.069	5.069	5.069	5.069
Iliacus	1.870	0.776	2.258	2.258	2.473	3.798
Psoas	1.687	0.679	2.163	2.163	2.312	3.224
GMAX	0.218	0.468	0.363	1.953	1.953	1.953

IV. DISCUSSION

According to Figs. 2 and 3, the results obtained in this study correspond to the results reported by Winter [27]. The difference between results is due to simulation parameters. While Winter's curves correspond to the mean joint torques of a group of subjects, our curves have been derived from analyzing one subject. Specially, the mass, moment of inertia, and geometry of the subject used in this study differ from those that correspond to Winter's study. We judged the difference between the results of our simulation and those by Winter to be tolerable because we were more concerned with the effect that muscle loss has on hip joint work. Assessment of results shows that they are also in accord with other reports [28].

As it can be seen in Table II, the work done by the hip joint of the transected limb is less than that of the intact one. From a simulation point of view, the hip and knee joints angle, the parameters of the model, i.e., mass and moment of inertia of the limbs, and also the muscle loss are the causes of the difference between results. To judge the effect of only muscle loss on hip joint work, all parameters should be the same except for muscles. To do so, intact model 2 is analyzed. From the comparison made between the work of the hip joint of this model and transfemoral model, it can be concluded that muscle loss due to transfemoral amputation leads to less work at hip joint. We speculate that this result is due to the role that hamstrings and rectus femoris (biarticular muscles) play during motion in the intact model. During swing, while they try to flex or extend the knee, they act as a hip extensor or flexor. Then, hip flexors and extensors should exert higher forces, and therefore, do more work, to produce the required hip motion. This result contradicts the empirical studies that found the energy expenditure of amputees is higher than those of able-bodied ([8]- [12]). But, the results presented in Table II, only describe the role of muscles. After amputation, the gait of a transfemoral amputee is affected by several parameters, namely, the input hip and knee joints angle, the mass and moment of inertia of the prosthetic leg, and the function of prosthetic components like foot and knee. Additionally, the energy expenditure should be calculated during whole gait cycle for all joints of the body, and then summed, and compared for transfemoral amputee and healthy models. The findings of the previous empirical studies reveal the effect of all these parameters on energy expenditure. But, from these studies, it is not possible to determine the effect of muscle loss. In our study, the effect of muscle loss on the work done by hip joint was explored.

Unexpectedly, for a transfemoral amputee, muscle loss does lead to less work in hip flexor muscles. Regarding the finding of experimental studies that reported the energy expenditure of a transfemoral amputee is more than that of a healthy subject, our results suggest that transected limb hip joint does not contribute in increased energy expenditure of a transfemoral amputee, during the swing phase of gait.

According to Table II, the work done by iliacus and psoas of a transfemoral limb is more than that of the intact limb. But, for gluteus maximus the work done in the transfemoral limb is less than that of the intact limb. As more hip extensors are removed from the model (transfemoral 2), the residual extensors (gluteus maximus) should do more work, but the work done by flexors is not affected. Also, as more flexors are removed from the model (transfemoral 3 and 4), the residual flexors should do more work. We speculate, while excluding more muscles from the residual limb does not change the total work at the hip joint, it lessens the efficiency of motion. This is because the more work done by residual muscles will be associated with more wasted energy (for example, in the form of heat). Experimental studies are lacking when relating energy expenditure to residual limb length in transfemoral amputees [29]. Nevertheless, the results presented in Table II for different amputee models are in line with the common practice in transfemoral amputation surgery according to which it is important to maintain the length of a residual limb as much as possible [7].

V. CONCLUSION

This paper presented a computer simulation of transfemoral amputee swing phase of gait. The effect of muscle loss on the work done at hip joint and by residual muscles was modeled. According to the results, the absence of biarticular function of hamstrings and rectos femoris leads to less work of the hip joint of transfemoral limb in comparison to that of an intact limb. Also, as more hip flexors or extensors are removed from the residual leg, the residual flexors and extensors should do more work.

To improve the simulation, research is underway by the authors. For example, imaging techniques such as computed tomography (CT) may be used to drive the more realistic attachment points of muscles. Also, in this study, the motion of the leg has been limited to sagittal plane. Including the motion in other planes will help improve the results of the simulation.

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