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Modeling and simulation of muscle forces of trans-tibial amputee to study effect of prosthetic alignment

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Abstract

Background. The muscle forces tend to change when any musculoskeletal system is damaged. It is necessary to predict and explain the patterns of muscle forces in the stump of a left trans-tibial amputee during walking, and to study the effects of the prosthetic alignment.

Methods. Musculoskeletal modeling and computer simulation were combined to calculate muscle forces in the trans-tibial lower limb during walking. The prosthesis was aligned to be in optimal position for the subject and then changed into +6° and −6° in the sagittal plane relatively. Kinematic data of the stump wearing a prosthesis and ground reaction forces were simultaneously recorded by a gait analysis system and a force platform, respectively. The data were input into a model of the lower trans-tibial extremity with three-dimensional geometry and the corresponding seven muscle forces were predicted by a static optimization.

Findings. Muscles performed much more actively in stance than in swing phase. Most muscles appeared very active around both heel-strike and toe-off. Muscle forces predicted were similar to that in temporal distribution at all three alignment conditions but the major muscles such as gluteus maximus, hamstrings, vasti and rectus femoris generated remarkable greater forces in −6° and +6° alignments than the normal condition.

Interpretation. The above results showed the muscle forces increasing at the mal-alignment. Because the incorrect alignment could break the relative position of the socket and foot, and that would generate the extra joint moments. As a result, muscle forces increased, and the long-duration fatigue occurs more easily. The finding suggests that the proper prosthetic alignment is very important for the stump muscles normal activities.

Keywords: Musculoskeletal model; Muscle forces; Prosthetic alignment; Trans-tibial; Joint loading

1. Introduction

Musculoskeletal system functions to sustain the human body, and drive it to perform complicated movements. In order to describe various musculoskeletal interactions, a lot of mathematic models have been established to research the complex of human movements, such as those models which were rough skeletal system in early days, and those ones in which the muscles were added reasonably. A musculoskeletal model essentially includes segments of body and a range of muscles which are attached to the segments. At present everyday movements, such as walking, jumping and so on can be reproduced in laboratory. The musculoskeletal modeling proves to be useful in a wide field of human biomechanics, and is mostly used to be predicting muscle forces, ligaments and articular loading (Onyshko and Winter, 1980; Davy and Audu, 1987; Pandy and Berme, 1988; Pandy et al., 1990; Kuo and Zajac, 1993). This method is considered as a unique muscle forces simulating technique nowadays, because Electromyography (EMG) of superficial muscles which is picked up by the surface

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electrodes (a non-invasive method) could not indicate the muscle forces direct. At present this method also plays an important part in studying the musculoskeletal interaction, muscles coordination and antagonism, and even neuromuscular control.

The balance and flexibility of the body could be disturbed by abnormal muscle forces. The abnormal muscle forces even lead the skeleton, muscle or alignment injuries. It has been proved that long-duration abnormal distribution of muscle forces would cause the fatigue and injury to muscles (Baidya and Stevenson, 1988; Gorelick et al., 2003). The muscular metabolic cost in an amputee's stump trends to increase badly because he/she has to use the remaining skeleton and muscles to drive a weight-bearing prosthesis on the amputated side, and would make the entire body fatigue from long walking. This also restrains the desired degree of rehabilitation (Joseph, 1995).

For the trans-tibial amputee, the pattern of muscle activities in the stump is affected by many factors. In previous studies, some experiments on one-footed vertical jumping of the trans-tibial amputee revealed that, the jump height is markedly reduced by energy transmission deficit in the stump muscles (Strike and Diss, 2005). An imaging method of evaluating the muscle metabolic activity, which uses the 2-[18F]-fluoro-2-deoxy-glucose positron emission tomography, explained the muscle compensation strategy during exquisite sports in the intact and amputated lower limb of trans-femoral amputees (Shinozaki et al., 2004). EMG signals of the stump are also used to investigate the correlation between the muscle activities and stump/socket interface stresses (Hong and Mun, 2005). Nolan and Lees' (2000) research compared the effect of walking speed on the pattern of muscle activities in the trans-femoral and trans-tibial amputees, in which EMG data of the stump were measured and evaluated.

Several texts have addressed that effect of a prosthesis on the pattern of muscle activities is important, such as how the muscle metabolic cost in the stump changes when the trans-tibial amputees walk with different prosthetic foots (Huang et al., 2001). One study of eight below-knee amputees (Winter and Sienko, 1988) also studied the synthetical biomechanical properties of the amputees, including EMG signals and metabolic cost in the stump, when they walk at different speeds with different prosthetic foots. Alignment is a key factor that affects the performance of a prosthesis, and likely to lead abnormal gait and limb fatigue. However today the alignment of a prosthesis is a trial-and-error process, which is very time-consuming, subjective and reliable on the prosthetist's experiences. Furthermore, the feedback from the amputee sometimes is equivocal. Knowledge of the abnormal pattern of muscles activities which is induced by improper alignment, could enable the progress of evaluative criterion. As walking is a main and basic activity in the amputee's daily life, it is important to study how much the pattern of muscle forces changes according to the alignment. Blumentritt et al. (1999) reported how the sagittal plane prosthetic alignment affects knee loads when the trans-tibial amputee is standing, and Jia et al. (2005) also carried out a series of experiments to study the influence of dynamic prosthetic alignment on plantar foot pressure when the trans-tibial amputee is standing.

As mentioned above, there are a few researches which were focus on the differences in the gait kinetic, ground reaction force, or joint moments attributed to the alignment. As well known that the force is connected to the movement direct, so the properties of an amputee's walk must be conducted by the pattern of the force generation and transmission inside the amputated lower limb. The muscle forces play an important role in such a complex process. So there is still some work needed to do to study the essence of why and how these characters are affected by the prosthetic alignment. Some studies evaluated the pattern of stump muscle activities by EMG signals. However, the EMG signals can only represent the tendency and regulation of muscle activities in quality, but are not the true muscle forces. It also remains unknown of the determinate function between the EMG signals and the muscle forces, and the non-invasive methods of measuring muscles forces remain impossible yet. In order to study more about how the alignment affects the pattern of the muscle activities when a trans-tibial amputee is walking with a prosthesis, the purpose of the research is to predict muscle forces in the trans-tibial amputated lower limb quantitatively, by developing a specific musculoskeletal model expanded upon previous musculoskeletal modeling. And the effect of prosthetic alignment on the pattern of the muscle forces is also studied.

2. Methods

2.1. Musculoskeletal model

Because the extension and flexion of the lower limb in the sagittal plane are much more important than the movements both in the frontal and transverse planes during walking, the adduction/abduction in the frontal plane and the internal/external rotation in the transverse plane of the hip and knee were ignored in this musculoskeletal modeling. The musculoskeletal model has two degree-of-freedom (DoF) in the sagittal plane, in which four segments represent the prosthesis, shank, thigh, and pelvis of the amputated lower limb (see Fig. 1a). The 2-DoF was the angles of the thigh and shank relative to the horizontal line. The patella-tendon-bearing socket of the prosthesis was supposed to attach to the stump firmly without any slippage or rotation, and the solid-ankle-cushion-heel foot was simplified as a particle of mass located at the extremity of prosthesis. Segment lengths L_i, segment masses m_i, segment mass centers L_{ci}, and segment inertial properties I_{ci} $(i = 1,\ldots,4)$ were based on the literature data (Pandy et al., 1990), especially the parameters of the shorten shank were revised by a scaling algorithm according to the subject's stump.