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Dynamic analysis of above-knee amputee gait

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Abstract

Background. It is important to understand the characteristics of amputee gait to develop more functional prostheses. The aim of this study is to quantitatively evaluate amputee gait by dynamic analysis of the musculoskeletal system during level walking and stair climbing.

Methods. Dynamic analysis using gait analysis, electromyography and musculoskeletal modeling for above-knee amputees ($n = 8$) and healthy adults ($n = 10$) was performed to evaluate the muscle balance, muscle force, and moment of each major muscle in each ambulatory task. Time–distance parameters and the kinematic parameter of gait analysis were calculated, and a root mean square electromyogram of major muscles and hamstring and tibialis anterior coactivity was measured using electromyography. Lastly, dynamic analyses of above-knee amputee gaits were performed using musculoskeletal models with scaled bones and redefined muscles for each subject.

Findings. Most kinematic parameters showed statistically no difference among the tasks, excluding pelvic tilt, pelvic obliquity, and hip abduction. Major muscle activities and coactivities of the hamstring and tibialis anterior showed that the stair ascent task needed more muscle activity than the stair descent task and level walking. The muscle activity and coactivity of amputees were greater than those of healthy subjects, excluding the hamstring coactivity during stair ascent ($P < 0.05$). Lastly, dynamic analysis showed that weakened abductor and excessive adductor and then inadequate torque during all tasks were quantitatively observed.

Interpretation. Dynamic analysis of amputee gait enabled us to quantify the contribution of major muscles at the hip and knee joint mainly in daily ambulatory tasks of above-knee amputees and may be helpful in designing functional prostheses.

Keywords: Above-knee amputee; Stair climbing; Level walking; Electromyography; Musculoskeletal model; Dynamic analysis

1. Introduction

Above-knee amputation surgery has been the standard method of treatment for most soft-tissue and bone sarcomas. In Korea, 3.9% of injured workers were reported to be above-knee amputees, according to the annual report of the Ministry of Health and Welfare for physically disabled persons. Above-knee amputees tend to wear the prosthesis–socket system, which enables them to ambulate functionally instead of orthoses such as a wheelchair, crutch, and so on. Therefore, after amputation surgery, the patients are requested to repeatedly practice level walking and stair climbing with their own prosthesis–socket system at the amputated part of the lower extremity to improve ambulation ability. But amputee gait, including level walking and stair climbing, is a problem for the elderly and infants because of feelings of insecurity and fear of secondary disorder. While the elderly and infants can overcome these obstacles by reducing gait speed, most

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amputees wholly rely on muscle condition at the dissected limb, called a stump. However, many amputees want to have more functional prostheses to speed up recovery time and activities of daily living (ADL) adaptation rather than to strengthen stump muscles. Thus, when investigating the characteristics of amputees during ADL, it is important to first understand the muscle volume and forces of them.

Muscle volume and forces of amputees were frequently observed in both management of post-surgical treatment for dissected muscles and muscle adaptation after rehabilitation therapy for ADL motion. The condition of the post-surgical muscles depends on the surgeons who perform the amputation surgery. Therefore, dissected muscles after surgery were needed to be re-estimated by MRI (Zhang et al., 1998) and sonomyography (Zheng et al., 2006). Muscle adaptation by an amputee's intact limb was needed to compensate for the lack of stump muscle force during ambulatory motion (Seroussi et al., 1996). Recently, it has also been reported that muscle adaptation for ADL motion depends on the amputated level of the lower limb (Schmalz et al., 2007). Therefore, it is necessary to redefine the muscle volume and force for dissected muscles to understand and analyze amputee gait. However, related research is rare. To improve the efficiency of rehabilitation therapy through amputee gait, integrated approaches are needed that consider not only muscle condition but also dynamic movement of the musculoskeletal system for amputees. However, there have been few studies conducted on amputee gait of patients with orthopedic implants and amputees with artificial limbs. Recently, several studies that considered musculoskeletal condition have been reported for healthy subjects (Heller et al., 2003, 2001), but research on amputees with prostheses is still rare. Therefore, musculoskeletal models of amputees with prostheses were needed to evaluate quantitatively the contribution of each muscle to amputee gait. The aims of this study were primarily to evaluate the muscle condition by acquiring the root mean square electromyogram (RMS EMG) and secondarily to predict muscle forces and moments using three-dimensional musculoskeletal dynamic models of above-knee amputees with prostheses for level walking and stair climbing tasks. In addition, we wanted to evaluate the habitual gait of above-knee amputees to keep pace with the gait speed of healthy persons by measuring muscle activity during two-stairs ascent and two-stairs descent tasks at one time.

2. Methods

2.1. Subjects

The experimental data were collected from eight above-knee amputees (right side) with lower-limb prostheses; each subject had displayed volume stability of the residual limb for at least 2 years and had no skin problem of the stump prior to participation in this study. They had used the same prosthesis for than 5 years on average. Ten healthy individuals served as the control group, free of any musculoskeletal or neurological dysfunction that would affect gait (Table 1).

Table 1
Subject characteristics mean (SD)

	AKA group ($n = 8$)	Control group ($n = 10$)
Age (yrs)	39.88 (7.83)	24.35 (1.73)
Height (cm)	168.01 (4.14)	174.65 (0.81)
Weight (kg)	67.56 (5.54)	64.46 (1.47)

2.2. Simulation procedures

2.2.1. Motion analysis

Motion analysis was performed by using a three-dimensional motion analyzer with seven infrared cameras (VICON 370, Oxford metrics Ltd., Oxford, UK) and two CCD cameras (HDV1080i, SONY, Tokyo, Japan). Fifteen 25-mm reflective markers for the sound limbs of the amputees and both limbs of the healthy subjects were placed on the sacrum, anterior superior iliac spine (SIS, bilaterally), lateral femoral epicondyle (bilaterally), calcaneous and malleolus (bilaterally), metatarsal head (bilaterally), and the lower lateral 1/3 surface of both shanks and thighs (bilaterally) using a wand, respectively. Marker placement on the prosthesis was estimated by using the bony landmarks on the sound limb. All kinematic data were sampled at 60 Hz using a personal computer.

Prior to the experiments, anthropometric measurements (height and weight) of the lower extremity were performed for all subjects (Table 1). Later, the subjects walked across the level walkway until they were accustomed to the level walking task. The healthy subjects walked barefoot while amputees walked with shoes and both walked at the self-selected speed on a 15 m gait pathway that was instrumented with two force-plates (900 mm × 600 mm, Kistler Instrument Corp., NY, USA) to measure the ground reaction force.

For stair climbing, a wooden staircase was custom-built. The staircase with an inclination of 30° included three stairs (height 160 mm, width 300 mm), and two piezoelectric force-plates (400 mm × 600 mm, Kistler Instrument Corp., NY, USA) were embedded in the second and third stair respectively to record the forces generated during stair accent and descent. And another force-plate was embedded on the ground level. Force plate data were sampled at 2500 Hz. The starting points for the stair ascending and descending tasks were in front of the staircase on the ground level and at the top of the staircase, respectively. The dominant foot of each subject was used during these tasks. We analyzed the stair climbing task for a stair stride cycle. During ascent, a stride cycle was defined starting with foot contact on the second step and ending at the next foot contact on the fourth step. During descent, the selected strides started with foot contact on the third step and ended with foot contact on the first step. Foot contact