Proceedings of BIO2006
2006 Summer Bioengineering Conference
June 21-25, Amelia Island Plantation, Amelia Island, Florida, USA

BIO2006-155802

REAL-TIME PATIENT-SPECIFIC ANALYSIS OF RESIDUAL LIMB STRESSES IN TRANSTIBIAL AMPUTEES DURING ERGOMETER EXERCISE

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INTRODUCTION

Transtibial amputation (TTA) patients spend more energy during daily activities such as standing, walking, ascending stairs and rising from a chair, than does a healthy person. Physical fitness of the patient lapses after the amputation. Without proper rehabilitation, poor physical fitness will inevitably lead to immobility, which endangers the residual limb and is a cause of serious morbidity and mortality among TTA patients. Therefore, the rehabilitation of prosthesis-users must aim at recovering and even increasing the fitness of the TTA patient [1]. Previous studies used a cycle ergometer, driven by the intact leg, and concluded that patients recovered their physical fitness after 6 weeks of training [1], however, in these endurance training sessions, patients did not use the residual limb for the cycling activity. A review of the management strategies for TTA patients highlighted the beneficial effects of early weight bearing [2]. Mainly, early weight bearing prevents knee contractures, reduces edema, and accelerates early prosthetic fitting and return to functional living. Despite these remarkable advantages of early weight bearing and physical activity of amputees, the biomechanical effects of active participation of the residual limb of a TTA patient in endurance bicycle ergometry were never investigated. This is a major open question in orthopaedic rehabilitation, since excessive mechanical stresses in the residual limb that may occur during bicycle ergometry can potentially injure internal soft tissues, through ischemia or excessive deformation. Therefore, our objective was to determine the stress distribution in the internal soft tissues of the residual limb in TTA patients during a cyclic ergometer exercise, using a real-time patient-specific modeling system [3].

METHODS

A simplified patient-specific finite element (FE) model of a slice through the residual limb was solved in real-time by employing a custom-made FE code [3] which calculates internal stresses in soft tissues continuously, based on time-dependant boundary conditions from force sensors at the limb-prosthesis interface. Four male unilateral TTA subjects (mean age 50.4, mean body weight: 91.6 Kg) volunteered for this study, after obtaining the approval of the local Helsinki committee at Sheba Medical Center. Critical heart rate was assessed for each patient using the arm ergonometry test. Dimensions of the bones and surrounding soft tissues of the residual limb were extracted from anterior-posterior and lateral x-rays. Seven thin (~0.2 mm) and flexible force sensors (FlexiForce, Tekscan Co. MA, USA) were taped to the residual limb at critical locations (tibial tuberosity, anterior and posterior distal ends of the tibia, end of fibula, distal gastrocnemius, and central gastrocnemius) before each patient donned his prosthesis. One additional sensor was placed on each pedal of the ergometer (Tunturi 604 ECB Pro trainer). A physiotherapist (AT) adjusted the seat height for minimal knee flexion of the patient during cycling and tied the prosthetic foot to the pedal. A physiologist recorded heart rate during the trials. Aerobic activity was halted when the heart rate exceeded the critical heart rate. Generally, subject cycled at their own chosen velocity with no ergometric resistance for up to 3 minutes, then rested for 2 minutes and continued cycling for an additional 3 minutes (Fig. 1). Two subjects walked on a treadmill (Woodway Co., WI, USA) after using the cycle ergometer. During each trial, the system calculated and graphically presented the internal stresses in the soft tissues of the residual limb, on-line, using the hardware and software described in our previous paper [3].

Fig. 1: Subjects riding an exercise bike (left) or walking on a treadmill (right), while the real-time FE system calculates and graphically presents the internal stresses

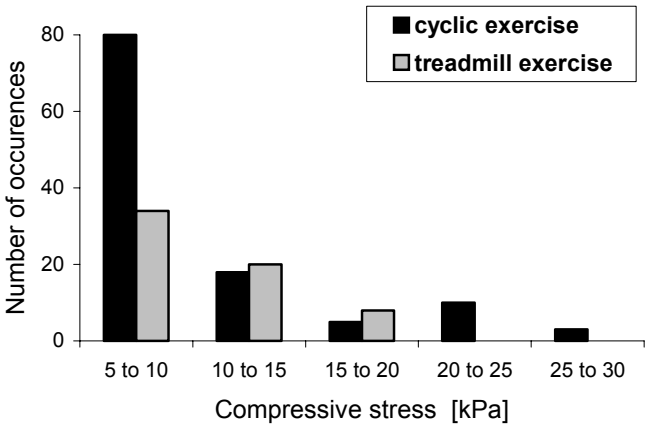

Fig. 2: Occurrences of peak compressive stresses at the anterior distal tibia for one transtibial amputee (with body weight of 55 kg) during 30 seconds of treadmill or cyclic

RESULTS

One subject, who was medicated for high blood pressure, was compelled to cease endurance cycling activity when he reached critical heart rate, and did not continue to a treadmill exercise. The residual limb of a second subject was scarred and moist. We therefore placed the force sensors at the liner/socket interface and not at the skin/liner interface but data from the force sensors in this setup were weakened. For the two patients who continued with treadmill walking after their cyclic ergometer endurance exercise, we found that peak principal compressive stresses in the soft tissues of the residual limb were approximately 1.5-fold higher during cyclic exercise compared with treadmill walking. Peak principal compressive and von Mises stresses during cycling appeared under the anterior distal end of the truncated tibia, whereas in treadmill walking, corresponding peak stresses occurred under the truncated distal fibula. The occurrence of peak principal compressive stresses at the anterior distal tibia of one patient is shown in Fig. 2 for both ergometer (maximal compression stress of 28 kPa) and treadmill (maximal compression stress of 19 kPa) exercises. Figure 3 shows the time-dependent distribution of von Mises stresses in the residual limb of that patient. Stress concentrations in soft tissues of the residual limb under the anterior distal tibia can be clearly identified (Fig. 3).

DISCUSSION

We found that real-time patient-specific FE analysis of internal stresses in the residual limb of TTA patients during cyclic ergometer exercise is technically feasible, and hence, this should be the subject of subsequent patient studies with a larger number of subjects. Comparing the distributions of internal stresses in the soft tissues of the residual limb during cyclic ergometry with those obtained during treadmill walking (in this study and in a previous study, [4]), it is evident that a walking activity mostly loads the muscle flap under the truncated bones, as opposed to cyclic ergometry, which mostly loads the soft tissues under the distal anterior surface of the tibia (Fig. 3). In closure, clinically monitored cyclic ergometer training can enrich the rehabilitation routines of TTA patients and bring patients closer to normal daily activities. However, further extensive research is necessary for developing training programs that will accomplish swift physical fitness recovery of TTA patients without compromising the health and integrity of the residual limb. The real-time patient-specific FE modeling system [3,4] is a powerful tool for achieving this goal.

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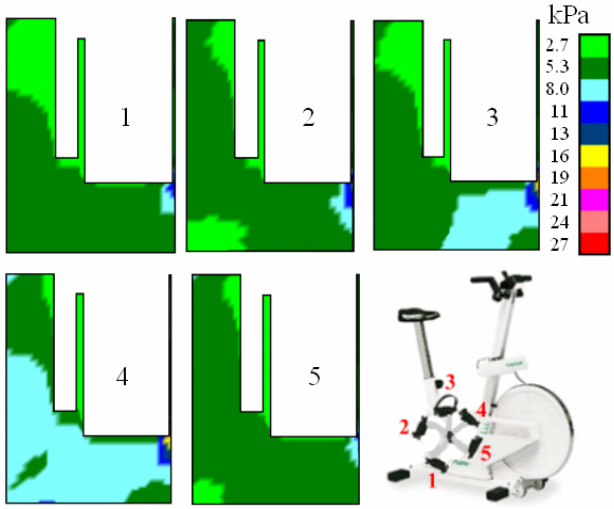

Fig. 3: Progression of residual limb von Mises stresses during one ergometry cycle of a transtibial amputee (body weight 55 kg).
Position of the pedal of the ergometer is shown for each stress state, on the right bottom frame.