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Simulative Analysis of Joint Loading During Leg Press Exercise for Control Applications

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Abstract: Leg extension is a multi-articular movement allowing flexibility of muscular activation and control. Therefore, joint loadings during leg press exercise can only be estimated using the whole reaction force vector together with the leg posture. A dynamic model of the musculoskeletal system as well as experimental data from a diagonal leg press are used to investigate external knee joint loadings and the influence of different orientations of the foot plate. Varying orientation in sagittal plane affects ankle, knee and hip loadings by changing the leg posture and the direction of the resulting force vector. Different orientations in frontal plane move the center of pressure of the force vector across the foot and thus change knee adduction and abduction moments. The results in this paper indicate, that high forces, which are required for an effective training, can be controlled using the foot orientation as manipulated variable. Thereby, unphysiological loadings and training-induced damage can be avoided.

Keywords: Dynamic model, Musculoskeletal model, Inverse dynamic problem, Manipulated variables, Robotics, Sensor system.

1. INTRODUCTION

Sarcopenia as well as loss of muscle strength and power are important factors compromising active independent aging (Narici and Maffulli (2010), Mian et al. (2007)). These factors are not only associated with an impaired motor performance during daily activities but also with an increased risk for the development of chronic age and wealth related diseases. Participating in regular physical activity, both aerobic and strength exercises, can slow down the physiological deconditioning associated with aging, and prevent or decelerate the development and progression of chronic disease. Muscular-skeletal disorders (MSD) are one of the most common cause of severe long-term pain and physical disability (Woolf and Pfleger (2003)). In Germany, 36.2% of the patients treated 2012 in inpatient rehabilitation centres, i.e. a total of 596000 patients, suffered from MSD, such as knee and hip arthrosis or osteoporosis (Statistisches Bundesamt (2013)).
Resistance training as a therapy for traumatic sports injuries (e.g. rupture of the anterior cruciate ligament) is already widely established. The use of training to increase or reduce the loss of muscle strength for osteoarthritic and or rheumatic patients is now also being seen as increasingly important, as muscle weakness due to atrophied and quickly fatiguing muscles can result in high joint loading (Karamanidis and Arampatzis (2009)). This in turn fosters joint inflammation and pain, thus influencing progressive joint degeneration. Even following endoprosthetic joint replacement, postoperative rehabilitation in a rehabilitation hospital or center as well as the subsequent outpatient phase involve consistent regular muscular resistance training. Thus, muscle strength training can be considered an important intervention for aging people to recover from or prevent the development and progression of MSD. However, there is a trade-off between training effectiveness and training-induced damage. Effective muscle strengthening requires high muscle forces on one side. On the other side, the control of these high forces is necessary to avoid unphysiological loading on the musculoskeletal system and to guarantee a safe training.
The leg press is one of the most common examples of training equipment prescribed for neuromuscular training of the leg extensor muscles. Most often, the horizontal force, movement velocity and range of motion are used as the only indicators for joint loading and training stimulus. However, leg extension is a multi-articular movement allowing flexibility of muscular activation and control. Monfeld (2003) clearly demonstrated in his study analysing knee extensor muscle strength in patients after cruciate ligament reconstruction, that a similar horizontal force does not necessarily imply similar muscular effort for the knee extensor muscles. Due to the different direction of the force vector, the joint moments for the ankle, knee and hip and thus the contribution of the leg extensor muscles differ considerably. In Fig. 1 the knee joint moment in the lower example is small and thus there is hardly no muscle force from the knee extensor muscles.

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The plate reaction force vector in frontal plane (Fig. 1, right)

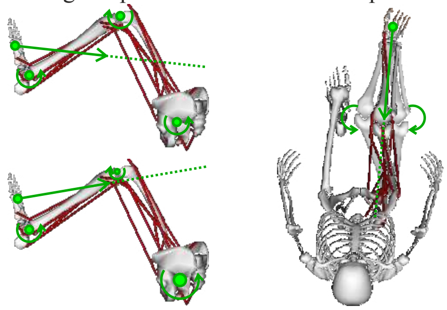

Fig. 1. Multi-articular movements allow for compensation mechanisms in sagittal plane (left). Inappropriate postures or varus and valgus deformities affect knee adduction and abduction moments in frontal plane (right).

highlights a cause for a potential training-induced damage. High external knee adduction moments reflect high compressive forces acting on the medial knee compartment (Kutzner et al. (2013)) and are supposed to foster osteoarthritis (OA) development and progression, when occurring during locomotion (Reeves and Bowling (2011), Andriacchi et al. (2004), Trepczynski et al. (2014)). Thus, training in the leg press with OA patients and elderly people should focus to reduce knee adduction moments. The magnitude of the knee adduction moment mainly depends on the magnitude of the reaction force and the moment arm of the reaction force about the knee joint center. One strategy to reduce adduction moments during locomotion are lateral or medial wedged insoles of 5 to 15° to induce a mediolateral shift of the center of pressure beneath the foot (Reeves and Bowling (2011), Kerrigan et al. (2002), Lewinson et al. (2014)). Therefore, it is supposed that during resistance training at the leg press a medial or lateral wedge influences mainly external frontal plane knee moments while a wedged support for heel or toe offset changes the geometry of the leg and influences the ankle, knee and hip extensor moments mainly in the sagittal plane.
These studies indicate, that effectiveness and safety of leg extension training can be improved by developing a novel robotic leg press device. The idea is to use mechanical models of the musculoskeletal system to estimate joint loadings and control these loads actively with the orientation and position of the foot plate as a manipulating variable. The evaluation of the orientation as a manipulating variable is presented in this paper.

2. DYNAMIC MODEL OF TRAINING SCENARIO

The software system OpenSim was used for the simulation of the training scenario. OpenSim is a freely available software for dynamic simulations, especially of the musculoskeletal system (Delp et al. (2007)). Multibody systems are modeled as rigid bodies with mass and inertia properties connected by different types of joints with up to six degrees of freedom (dof). Movement coordinates are defined with respect to the joint coordinate system and can be actuated either directly by defining a corresponding force or torque or in case of the musculoskeletal system by muscle models.
The whole training scenario consists of a lower extremity model and a leg press model. Together they build up a closed kinematic chain. As rigid bodies in OpenSim can only have one parent body, closed kinematic chains are coupled by constraints, here by a constraint between the foot and the leg press plate.

2.1 Musculoskeletal Lower Extremity Model

The Gait 2354 model from OpenSim was used as a basic musculoskeletal model of the lower extremity. It consists of twelve rigid bodies, 54 muscles and 23 dof, whereas each leg has seven dof as shown in Fig. 2. Detailed information of

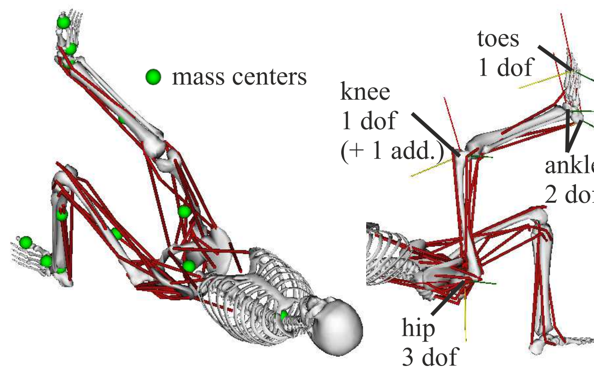

Fig. 2. Musculoskeletal model with twelve bodies and seven dof for each leg.

this model can be found in the OpenSim documentation [1].

2.2 Model Extension

The lower extremity model is needed to solve the inverse dynamics problem and determine the generalized torques from the equations of motion $M(q)\ddot{q} + C(q, \dot{q}) + G(q) = \tau$, where $q, \dot{q}, \ddot{q}$ are the generalized positions, velocities and accelerations of each dof, $M(q)$ is the mass matrix and $C(q, \dot{q})$ and $G(q)$ are the vectors of the Coriolis and gravitational forces, respectively. In sagittal plane there is at least one dof per joint, and so the loadings for hip, knee and ankle joint for each dof result from the inverse dynamics calculation. For frontal plane moments, one possibility is the calculation of muscle forces from the generalized torques (Sritharan et al. (2012)). But as individual muscle forces are not explicitly needed in further calculations, the basic Gait 2354 model is extended by an additional dof for the knee adduction as shown in Fig. 3. This coordinate is fixed to zero degrees, so that no movement occurs, but by solving the inverse dynamic problem, the external adduction moment is delivered, directly.
The second extension is the definition of a reference coordinate system for the contact constraint of the foot with the leg press plate. It is assumed that if the contact force between foot and plate is high enough, there is no motion of the foot on the plate. The contact plane has a fixed orientation with respect to the calcaneus as shown in Fig. 3. The origin of the coordinate system is positioned in

[1] http://simtk-confluence.stanford.edu:8080/display/OpenSim/Gait+2392+and+2354+Models, accessed: 02/2015