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Dynamic simulation of tibialis posterior tendon transfer in the treatment of drop-foot

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ABSTRACT

An extensive range of studies have been performed to describe kinematics and dynamics of human movements. However, the forces and moments generated by muscles are not measurable. Dynamic simulations are needed to estimate internal loading of the musculoskeletal system, to establish scientific basis of treatment planning before performing the surgery, and to predict the functional consequences of treatments. In this study, an ankle joint model consisting of 30 bones and 12 muscles was generated by using lower extremity model of OpenSim software. Muscle insertion points were virtually re-defined for simulation of tendon transfer operation of tibialis posterior in treatment of drop foot deformity. Flexion and inversion moments of ankle, and moment arm distances of tibialis posterior before and after operation were investigated comparatively. Tibialis posterior provided the dorsal flexion moment up to 28 N m after transfer, while providing the plantar flexion moment of −14.5 N m before transfer. Moment arm distance became average 33 mm after transfer, while it is average −11 mm before transfer. These increases provided the active dorsal flexion as the treatment of drop foot.

1. Introduction

Coordinated movements of human body are very complicated movements generated with the participation of many elements of the musculoskeletal system. An extensive range of studies have been performed to describe kinematics and dynamics of these movements, and anatomical/mechanical properties of the musculoskeletal system elements (e.g., muscle, tendon, bone, cartilage and ligament). Clinicians have examined the neuromuscular excitation patterns and movement kinematics in thousands of individuals with movement abnormalities before and after treatment interventions [1]. However, important variables are not generally measurable and it is difficult to establish cause–effect relationships in complex dynamic systems by using experimental data alone. Therefore, a theoretical framework combined with experiments are needed to provide estimates for the internal loading variables of musculoskeletal system (i.e., muscle forces and joint torques that are not measurable experimentally), to determine how neuromuscular impairments result in abnormal movements, to establish scientific base for treatment planning of abnormal movements, and to predict the functional consequences of treatments. Such a framework providing these gains can be obtained with the models and dynamic computer simulations describing anatomical structure of the musculoskeletal system elements and kinematics/dynamics of multi-jointed actions. Cause–effect relationships between the muscle forces, joint torques and body movement patterns can be determined with these models and dynamic computer simulations.

In this sense, tibialis posterior (TP) tendon transfer approach for the treatment of the drop-foot deformity, that is one of the

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most common walking deficiencies, was investigated in this study within the framework of dynamic computer simulation model. Drop-foot deformity is a posture disorder of the foot that occurs as the form of being plantar flexion position constantly in the swing phase of walking. Common reasons of drop-foot deformity are the peroneal nerve injuries, stroke, neuropathy, leprosy, diabetes, herniated disk sequellae, tumor resection and sequellae of injection. Peroneal nerve palsy after a trauma results in weakness or absence of dorsal flexion of the foot and toes which leads to the characteristic drop-foot and foot slapping at the end of the stance phase.

Due to the absence of the dorsi-flexor muscles, the foot strikes to the ground with a plantar-flexed ankle joint. The dorsal flexion of the ankle during the swing phase is not provided by any muscular activity, and this movement occurs only passively during the stance phase in which the foot rests on the ground [2]. Patients with drop-foot cannot lift up their foot enough in swing phase. This increases the falling risk and the metabolic energy consumption especially in activities where the lifting of the foot is more important (e.g., walking on soft ground, stair climbing and slope walking). In order to lift their foot from ground sufficiently, they need doing the excessive hip and knee flexion that can cause the pelvis tilt. In addition, sole strikes to the ground with sound, due to lack of dorsal flexion making ability, immediately after heel contact at the beginning of stance phase. Impaired walking and reduced mobility affect the life quality of patients with drop-foot deformity negatively.

The major aim of drop-foot treatment is the restoration of walking gait by providing passive/active dorsal flexion of foot. In addition to gait restoration, to prevent secondary injuries in some cases such as plantar ulcers and amputation in leprosy can also be included among the aims of drop-foot corrections. The main treatment options being applied are the usage of ankle-foot orthosis, functional electrical stimulation and TP tendon transfer. The ankle-foot orthosis supports ankle joint by wearing on foot, prevents excessive plantar flexion more than neutral position, and prevents toes striking to the ground. It is reported that the impedance control of an actively controlled ankle-foot orthosis reduces the slap foot occurrence, and makes the ankle kinematics in the swing phase more closely resembled normal individuals as compared to the zero and constant impedance control schemes [3]. As for that, functional electrical stimulation is a treatment approach providing the improvement by creating electrical stimulation at appropriate intervals with electrodes placed over the peroneal nerve. It can be used for the treatment of drop-foot incidents caused by upper motor neuron diseases. The connection between the peroneal nerve and dorsi-flexor muscles must be preserved for that this method can be implemented. In the traumatic cases that the peroneal nerve was destroyed, this approach does not work and TP tendon transfer method is emerged as an important alternative for treatment of drop-foot.

TP tendon transfer approach was handled separately in next section due to that it is the main treatment option related the topic of this study. The ankle joint model prepared in OpenSim, that is existing software in the field of dynamic simulations of musculoskeletal system, was also introduced in next section. The aim of this study is to emphasize the potential of dynamic computer simulations by introducing TP tendon transfer simulation performed in the software mentioned above.

2. Materials and methods

2.1. *TP tendon transfer*

It was introduced for the first time in the middle of the last century which encouraging results in the surgical correction of drop-foot can be obtained by transposition of the TP tendon to the anterior [4]. It is now widely accepted method, and frequently performed for gait rehabilitation in subjects with drop-foot deformity, as well as the examples such as rectus femoris transfer in the treatment of stiff-knee gait [5–8], hamstring transfer in the treatment of crouched-gait [9,10], and extensor carpi ulnaris transfer in the treatment of wrist joint posture impairment [11–13]. The transposition process TP tendon to the dorsal part of the foot in cases of lacking or poor functionality of the dorsi-flexor muscles is an often reported surgical operation in literature [14–21]. Andersen [22] reported that the excellent or good results were seen in 72 of 108 cases of TP tendon transfer. Srinivasan et al. [23] discussed the results of drop-foot operations realized in their institute, and reported that the TP muscle works well as a dorsi-flexor when transposed forwards irrespective of the method used. Steinau et al. [24] evaluated the long-term results of TP tendon transfers for drop-foot correction. They reported that their clinical follow-up study demonstrates the high patients' satisfaction, tolerable donor site morbidity, low necessity for additional orthotic devices, and low complication rates. Reis et al. [25] made a study to access the postoperative functional results of TP tendon transfer for drop-foot as a consequence of nerve palsy in leprosy. They stated that the tendon transfer method in leprosy is efficient in restoring normal function of the foot and gait. Goh et al. [26] investigated the effect of tendon insertion site in a biomechanical study by applying tendon transfer operation to the cadaveric legs. They measured ankle and foot motions of the specimens mounted on a mechanical testing machine, and compared the efficacy of both subcutaneous and interosseous routes. They reported that the interosseous route is more effective in achieving maximum dorsal flexion with minimal pronation.

TP tendon transfer operation is preferable to obtain dorsal flexion of the ankle and to eliminate TP's unopposed deforming force emerged on the medial side of foot, when clinical consultation and EMG data suggests that the peroneal nerve was damaged without chances of recovery. The dorsal flexion movement of the ankle is modified by the transposition, and normalization in parameters (i.e., the step length, the duration of step, and the average speed of the foot) is obtained compared to the preoperative evaluations.

TP tendon transfer is being implemented through the interosseal membrane between the tibia and fibula. The tendon is passed through the interosseal membrane and inserted in an osseous tunnel on the second or third cuneiform. The interosseal transfer gives a minor but sufficient range of movement of the ankle joint. TP tendon transfer is also being implemented through the circumtibial route (i.e., around the tibia) with three incisions that are on the medial side of the foot, medial side of the shank and dorsal side of the foot. After transferring dorsal side of the foot through a subcutaneous tunnel, TP tendon is being implanted to the tendons of the tibialis anterior, extensor hallucis longus, extensor digitorum