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ANALYSIS OF THE HUMAN ANKLE IMPEDANCE FOR THE DESIGN OF ACTIVE SOFT ORTHOSIS

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SUMMARY

Understanding the dynamic behavior and biomechanical properties of the ankle-foot complex is critical to several applications. Detailed insight into the function of the human ankle is the basis for the development of the ultimate goal of this project: a soft, skin-tight orthosis, dynamically and kinematically compatible with the joint in order to correct dropfoot pathology.

The main purpose of this study is to analyze the impedance of the ankle-foot system during normal walking gait. The analysis was performed using theoretical and experimental gait data. Besides the traditional gait lab data based on optical markers, a high-speed camera is also used to reveal further detail of the ankle joint.

INTRODUCTION

Dropfoot is a condition that results from a neurological deficit where there is a reduced or inexistent activity of the dorsiflexor muscles. This disorder causes an inability to perform the dorsflexion movement i.e. to raise the foot at the ankle which results in two major complications for the individual: first the foot slaps the ground after heel-strike on every step (foot slap); the second complication is the drag of the toes on the ground during swing phase (toe drag) [1]. The use of ankle-foot orthoses (AFOs) is the most common solution for the correction of this pathology.

Focusing on the foot contact with the ground, Winter developed a foot model for the stance phase of gait, where the foot ground contact is described in terms of viscoelastic elements [2, 3]. To understand what is happening in which phase of gait, Winter calculated different variables such as intersegmental torques, work, mechanical energy and power using Newton's laws and the energy conservation law. Palmer characterized the ankle function in the sagittal plane during stance phase of normal walking and for different speeds [4]. With his work, a model structure was developed consisting of the simplest combination of mechanical elements (spring-damper) that could reproduce the kinematic and kinetic patterns observed in the ankle data

The goal of this study is to re-analyze the biomechanical impedance of the ankle-foot complex during a normal walking gait to assist us in the design of a compliant ankle-foot orthosis, inspired by the skin deformation during motion [5], and embedded with active materials. Since drop-foot mainly affects the first period of stance (controlled plantarflexion) and swing phases, this is where our analysis is focused.

METHODS

To study the impedance of the ankle, three major kinetic and kinematic variables are considered: ankle joint angle, ankle joint angle rate of change and ankle joint torque. The theoretical data relative to ankle kinematics and kinetics were obtained from published tables for a normal ankle movement during a gait cycle [3].

The experimental data was collected as part of a previous work developed at IDMEC, Instituto Superior Técnico [6] and only a brief summary of the procedure and setup are given here. Subjects walked barefoot at their self-selected normal speed. The acquisition of the kinematic data was made using Qualysis Motion Capture System (Gothenburg, Sweden), with four ProReflex cameras. To acquire the external forces data, it was used three AMTI-OR6-7 force platforms (508mm x 464mm) (Newton, MA). To calculate the joint torques, an inverse dynamics analysis was performed using the kinematic data and the ground reaction forces (from the force platforms). For this study, we used data from 10 healthy subjects (5 males and 5 females). As sign conventions, we assumed as zero ankle position the anatomical reference position for the ankle; positive ankle position for dorsiflexion and positive ankle torque for plantarflexion torque.

To obtain detailed images of the ankle during stance, a high speed EoSens CMOS Camera from Mikrotron (Unterschleissheim, Germany) was used to record the motion of the ankle of a healthy male subject during natural movement at 100 frames (1280×1024 pixels) per second.

In this research, we characterize the ankle function analyzing in detail the curves that describe the ankle angular positions, velocities and torques over time, while taking visual insight from the high speed image capture.

RESULTS AND DISCUSSION

The preliminary kinetic and kinematic data (Fig. 1 and Fig 2) analysis reveals the spring-like and damper-like behavior of the ankle in the sagittal plane, as well as power input and power output at the ankle. Theoretical and experimental data obtained are consistent with each other and in this work we will only present and discuss the results for the theoretical data for a 56kg healthy female [2]. Figure 1 and 2 show graphs with clockwise and counter clockwise rotations, which suggests the periods where it is necessary to dissipate or accumulate energy respectively. Figure 3 shows critical points during the controlled plantar flexion, revealing that the maximum ankle plantar-flexion occurs before toe-strike. The motion between maximum angle of plantar-flexion (t=6.6s) and instants before toe-strike (t=7.0s) consists of a rigid body rotational motion about the heel, which is provided by flexion of the knee.

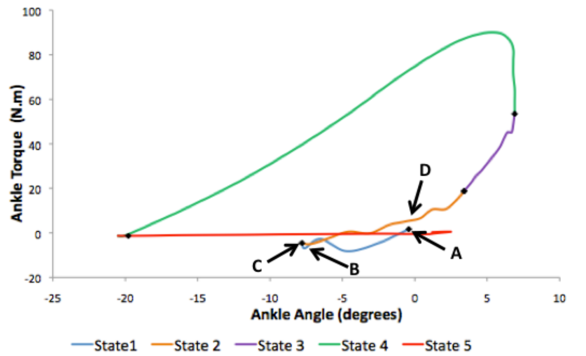

Figure 1: Ankle joint angles vs ankle torque during a gait cycle in natural cadence

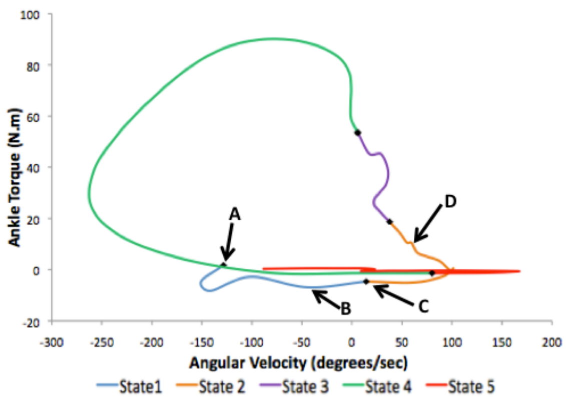

Figure 2: Angular velocity vs ankle torque during a gait cycle in natural cadence

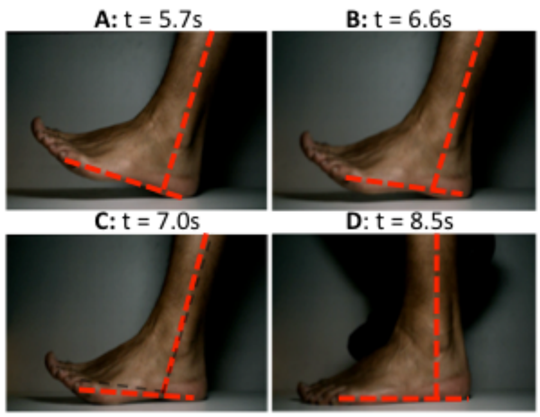

Figure 3: Images of the first period of stance obtained with the high-speed camera during motion

By observing the initial phase of stance (State 1) presented in Figure 1, we can conclude that the ankle acts as a torsional spring so we are able to estimate the appropriate stiffness of the elastic material that the soft orthosis will be made of. The expected relationship between the ankle torque and ankle angle is:

$$\tau = k\theta \quad (1)$$

where τ is ankle torque, θ is ankle angle, k is the spring stiffness. By simple linear regression, it's possible to determine k parameter. For instance, for the data of Figure 1, a good approximation for the angle/torque relationship for this subject is 133 N.m/deg.

Once we set the stiffness parameter of the elastic material, we then can augment it with the damping behavior of the active material, according to:

$$\tau = k\theta + \beta\dot{\theta} \quad (2)$$

where β is the damping parameter and $\dot{\theta}$ is the angular velocity. β is a variable value that will be function of the active material properties that we can manipulate through a given input.

CONCLUSIONS

The biomechanical analysis of the ankle-foot function is essential for the control system parameters of the orthotics under development. By identifying the spring-like and damper-like behavior of the ankle joint, it becomes clear to choose the most appropriate values of the components that will be part of the ankle-foot orthosis. The ankle torque/angle relationship can give us an important direction on the selection of the elastic material but it is important to note that the stiffness of the material should not exceed this value otherwise the ankle will not be able to perform the movements not affected by the pathology due to the inability to compensate the extra stiffness of the elastic material.

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