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VALIDATION OF AN INSTRUMENTED WALKWAY DESIGNED FOR ESTIMATION OF THE ANKLE IMPEDANCE IN SAGITTAL AND FRONTAL PLANES

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ABSTRACT

Recently, the authors designed and fabricated an Instrumented Walkway for the estimation of the ankle mechanical impedance in the sagittal and frontal planes during walking in arbitrary directions [1]. It consists of a powered platform; therefore, the users do not need to wear or carry any measurement device or actuation system other than reflective markers used to record the ankle kinematics with a motion capture camera system. This paper describes the continuous development of the Instrumented Walkway and presents an experimental preliminary validation of its capability to estimate the impedance of a system with time-varying dynamics. To validate the system, a mockup with mechanical characteristics similar to a human lower-leg and controllable time-varying stiffness was used. The stiffness of the mockup was estimated with fixed and time-varying stiffness. With fixed stiffness, a stochastic system identification method was used to estimate the mockup's impedance. When the mockup presented a time-varying stiffness, a second order parametric model was used. The RMS error between the two methods was 2.81 Nm/rad (maximum 4.12 Nm/rad and minimum of -3.41 Nm/rad). The results show that the proposed approach can estimate the stiffness of systems with time-varying dynamics or static dynamics with similar accuracy. Since the setup was already validated for systems with time-invariant dynamics, it concluded the system's applicability for time-varying systems such as the human ankle-foot during the stance phase.

INTRODUCTION

The estimation of the mechanical impedance of the human ankle has been the focus of research since it provides insight on the mechanical properties of the ankle and how it interacts with the environment. The ankle is the first major joint to interact with the ground during walking and it plays a major role in propulsion and stability, while generating torques and angles in all anatomical planes. The impedance of the ankle continually changes during walking to accomplish its task, and the way it changes depends on the type of gait. The impedance of a system correlates the output torque due to an input disturbance, and for a second order system, it is a function of the system's mass, damping, and inertia. The human ankle is capable of impedance modulation by muscle contraction of the muscles involved on its operation. Impedance controllers are often used in prosthesis, as it allows the device to mimic the mechanical properties of the human limb. For an ankle-foot prosthesis, the quasi-static impedance of the ankle in the sagittal plane has been used [2-4]; however, for proper control of the prosthesis, there is strong evidence that time-varying and task-dependent impedance modulation of the ankle is necessary [5, 6]. Activities of daily living (ADLs) include gait scenarios that require significant modulation of the ankle impedance in all anatomical planes, mainly in Inversion-Eversion (IE) and Dorsiflexion-Plantarflexion (DP) [5, 6]. These activities include but are not limited to turning, traversing slopes, and adapting to uneven terrain profiles. Some of these ADLs require 8% to 50% of turning steps depending on the activity [7].

To properly mimic the human ankle function, an understanding of the human ankle impedance is necessary. The dynamic impedance [8, 9] and quasi-static impedance [10-12] of the human ankle in both DP and IE were studied in non-load bearing conditions. However, non-load bearing conditions do not properly represent the ankle function during walking. Recently, two studies have reported the estimation of the mechanical impedance of the human ankle during gait. A mechatronics platform capable of applying ankle perturbations in one DOF in the sagittal plane was developed by Rouse et al. [13]. The perturbations were applied at four distinct points from 13% to 63% of the stance phase showing the ankle stiffness increased from 1.0 Nm/rad/kg to 4.6 Nm/rad/kg in this range. The damping increased from 0.012 Nms/rad/kg to 0.038 Nms/rad/kg in the same range. This study shows great variability of the ankle mechanics, but it was limited to one DOF and to a limited region of the stance phase. A different study by Lee et al. used a wearable rehabilitation robot, Anklebot, to apply ankle perturbation in two DOFs – DP and IE – while the human subject walked on a treadmill [14]. This study allowed for the estimation of the ankle impedance in two DOFs during the pre-swing, swing, and early stance of the gait. While this work provided insight on the ankle impedance during the swing phase, the amount of power supplied by the Anklebot's actuators were limited. Additionally, the experiments required the user to carry the weight of the Anklebot, potentially altering the walking dynamics. Moreover, the users were required to walk on a treadmill.

Previous work developed by the authors described the design and fabrication of an Instrumented Walkway capable of continuously applying pseudo-random perturbation to the ankle in two DOFs during the entire stance phase of the gait [1]. The developed vibrating platform to be used in the Instrumented Walkway does not require the user to wear or carry any actuator other than reflective markers for motion capturing using a camera system. The platform was designed to allow the estimation of the ankle impedance during walking in arbitrary directions such as different types of turning steps. Its construction and a preliminary evaluation to validate its capability to measure the stiffness of a mockup with time-invariant dynamics was presented. It was shown that the Instrumented Walkway was capable of properly estimating the stiffness of the mockup in two DOFs with less than 5% error.

This paper describes the continuation of the authors' work presented in [1] and validates the capability of the system to obtain the ankle time-varying impedance properly. First, the construction of the Instrumented Walkway presented in [1] is briefly described. Next, the construction of a mockup with mechanical characteristics similar to the human lower leg and active time-varying stiffness is described. Additionally, the paper describes an experiment where the mockup was first set with constant stiffness values, and its impedance was estimated using stochastic system identification methods. The results from this test were used for comparison to a second test, where the mockup was set with a time-varying stiffness and a second order parametric model was used to estimates mockup time-varying stiffness.

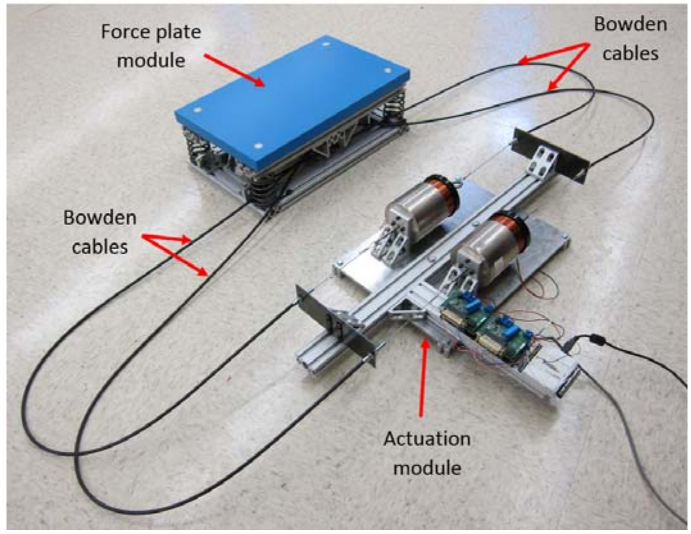

Fig. 1: Vibrating platform and its main modules.

INSTRUMENTED WALKWAY

An Instrumented Walkway was designed and fabricated for estimation of the ankle mechanical impedance during walking in arbitrary directions [1]. The Instrumented Walkway consists of vibrating platform (Fig. 1) installed on a walkway. The vibrating platform consists of two independent modules connected by Bowden cables. This allows the platform to have a very low profile for ease of installation on walkways. The actuation modules contain two voice coil actuators (Moticont® GVCM-095-089-01), each capable of generating ±351.3 N of force at 10% duty cycle or ±111.2 N continuously and have a 63.5 mm stroke length. The force plate module consists of a force plate (Kistler® 9260AA3) mounted on a frame supported by an universal joint, allowing the force plate to rotate in two DOFs, which are equivalent to DP and IE when the foot is on top of the force plate. Each corner of the force plate has a spring, which results in a rotational stiffness of the force plate of 270 Nm/deg in DP and 150 Nm/deg in IE. The springs maintain the force plate horizontally, allowing a subject to walk on it. The motors generate forces, which are transferred to the force plate module by Bowden cables, generating torques up to 168 Nm in DP and 26 Nm in IE. The force plate motion is transferred to the `human ankle during experiments. A motion capture system consisted of 8 Prime 17W OptiTrack cameras were mounted in a square formation covering a volume of about 9 cubic meters and an area of 9 square meters. The camera system was used to record the mockup's rotations.

MOCKUP DESIGN

To validate the capability of the Instrumented Walkway to evaluate the dynamics of a system with time-varying impedance, a mockup with mechanical characteristics similar to the human leg and time-varying stiffness capability was fabricated (Figures

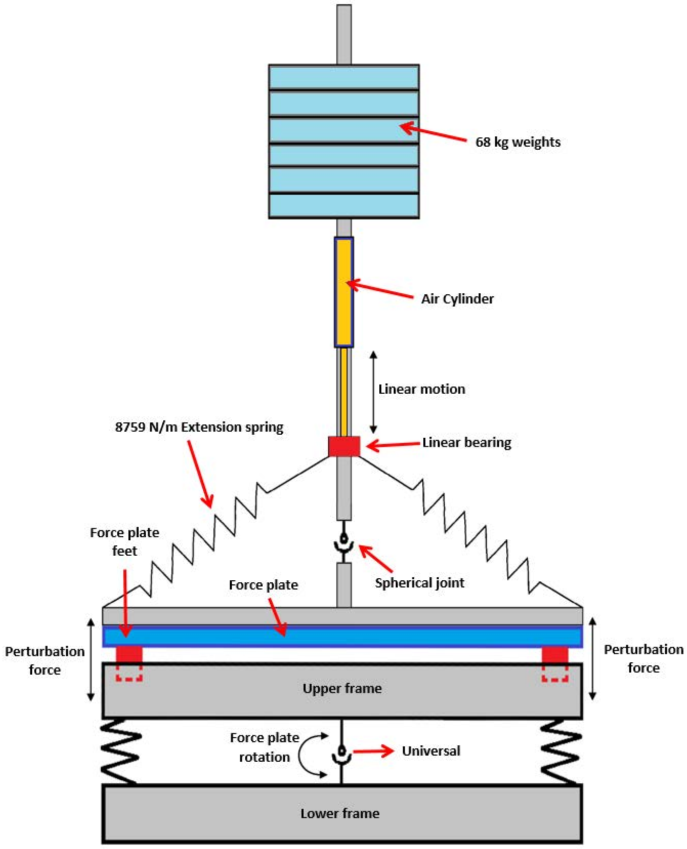

Fig. 2: Side view schematics of the mockup and force plate module. The actuation module generates forces that cause the force plate to rotate and apply perturbation to the mockup in two DOFs.

2 and 3). The mockup consists of a base and a vertical bar, which resemble foot and shin, respectively. A spherical joint connects the foot and shin and is located 0.1 m above the force plate to mimic the distance from the human ankle to the force plate. On the shin, there is 68 kg of weight at 0.8 m above the spherical joint, to emulate the inertia of an average human. The foot has four horizontal bars spaced 90º apart and it weighs 1.5 kg, which is comparable to the human ankle-foot mass [15]. Based on the foot geometry and mass, the mockup moment of inertia in both axes was calculated as 0.016 Nms^2/rad.

In one axis of rotation of the mockup, two of the horizontal bars parallel to each other are attached to the shin using chains and springs (one at each bar) with stiffness of 1925 N/m. These springs are attached with a pre-load to assure they are always under tension, and they generate a constant stiffness of 230 Nm/rad in one DOF of the mockup. In the other axis of rotation of the mockup, two of the horizontal bars parallel to each other are attached to a linear bearing using springs (one at each bar) with stiffness of 8759 N/m. These springs are also attached with a pre-load to assure they are always under tension. The linear bearing is attached to the shin vertically, and the springs are attached to the linear bearing. The linear bearing can slide vertically, and it is powered by an air cylinder with a stroke range of 0.114 m, and a cross-sectional area of 0.002 m^2. The cylinder

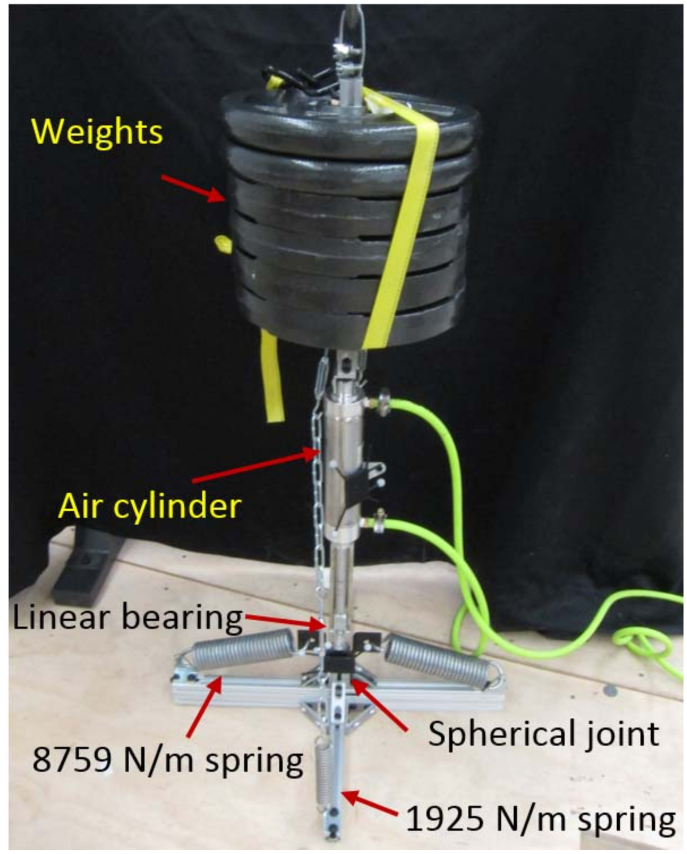

Fig. 3: Mockup and its main components.

was operated with air pressure at 369 kPa for a maximum force of 1380 N. The speed of the air cylinder was controlled using manually tuned exhaust port flow controllers, and the direction was controlled using solenoid air control valves connected to a remote computer. When the air cylinder is fully extended (Fig. 4), the moment arm (the distance between the spring attachment point to the shin and the spherical joint) and the springs pre-load are at their minimum, generating the minimum stiffness possible in the mockup. When the air cylinder is fully contracted (Fig. 5), the moment arm and the springs pre-load are at their maximum, generating the maximum stiffness possible in the mockup. This arrangement allowed the stiffness of the mockup to be controlled in one DOF by controlling the air cylinder position, which was estimated experimentally to be in the range of 91 Nm/rad to 226 Nm/rad as described in the next section.

Although the springs add stiffness to the mockup in both axes of rotation, the stiffness is not enough to balance the mockup under perturbation. To balance the mockup, a spring rated at 3750 Nm was added in line with the shin above the weights. This way, if the mockup leans in any direction, this spring generates a torque effectively balancing the mockup. This restoring torque is an unmeasured input to the system, potentially creating artifacts in the results. The rotations of the foot and shin, and the displacement of the actuator were recorded using the motion capture system, by placing the reflective markers on the shin, foot, and at the actuator.

Fig.4: Mockup at its minimum stiffness arrangement.

Fig.5: Mockup at its maximum stiffness arrangement.

To calculate the torque applied to the mockup's ankle, the moment arms between the ankle center of rotation and the foot center of pressure, and the reaction forces measured with force plate are required. The ankle center of rotation was calculated based on the average position of the two reflective markers placed symmetrically on both sides of the spherical joint, averaged at each sample time as described in [16]. The center of pressure on the mockups foot can be obtained from the force plate readings, and the moment arm is the vector from the center of pressure to the spherical joint's center. The ankle angles were calculated as the relative motion of the foot with respect to the shin, based on the position of these elements obtained from reflective markers placed on them.

QUASI-STATIC STIFFNESS ESTIMATION

The stiffness of the mockup was estimated at four fixed positions of the air cylinder ranging from its maximum extension to 0.042 m below the maximum extension. This range was chosen so the pre-load of the springs assure the springs are on their linear range of operation. The stiffness was estimated as described in the previous work, where stochastic methods were used to estimate the mechanical impedance of the mockup [1].

The stiffness of the mockup at each actuator position was estimated by generating uncorrelated pseudo-random torque perturbations at each actuator with a bandwidth of 30 Hz, resulting in perturbations being applied to the mockup on both of its axis of rotation, equivalent to DP and IE of a human ankle. The data was sampled at 300 Hz by the camera system, and the force plate sampled the reaction force at 7200 Hz (down-sampled to 300 Hz in post-processing to match the camera system data). The impedance was calculated based on the angles and torques of the mockup, similar to the method described in previous work [1]. In summary the admittance *Y(f)* is defined as a transfer function correlating torque inputs *τ(f)* to displacement outputs *θ(f)*:

$$\theta(f) = Y(f)\tau(f) \tag{1}$$

and its inverse is the impedance *Z(f):*

$$Z(f) = \frac{\tau(f)}{\theta(f)} \tag{2}$$

The ankle angles *θ(f)* and torques *τ(f)* were measured during each experiments, and the Matlab's® built in function *tfestimate* was used to calculate the impedance *Z(f).* The function *tfestimate*, finds a transfer function based on the quotient of the cross power spectral density of the torques and angles and the auto power spectral density of the torques. The *tfestimate* was implemented with a Hamming window of 512 samples, 50% overlap, and evaluated with a fast Fourier transform length of 1024 samples. The resultant impedance has a spectral resolution of 0.19 Hz. The coherence between the input angle and output torque was calculated with the Matlab's® function *mscohere* with the same parameters as the *tfestimate* function. The *mscohere* is a function of frequency with values between 0 and 1 that indicates how well the input correlates to the output at each frequency. The estimated impedance and coherence at the four air cylinder positions can be seen in Fig. 6.

The stiffness were estimated from the magnitude plots at 0.9 Hz as 89 Nm/rad, 128 Nm/rad, 197 Nm/rad, and 230 Nm/rad for air cylinder displacements of 0 m, 0.0151 m, 0.0300 m, and 0.0415 m, respectively. The 0.9 Hz frequency was chosen as it showed high coherence (above 0.88) for all tests and it represents the stiffness of the mockup before the inertia and damping have any major effect on the impedance magnitude. A third order polynomial was fit to the mockup's stiffness and air cylinder position (in a least-squares sense) using the Matlab® *polyfit* command. The polynomial correlates the stiffness measurement to the position of the air cylinder; therefore, during motion of the air cylinder, the stiffness of the mockup can be estimated solely based on the position of the air cylinder. A third degree polynomial was used to account for nonlinearities in the relationship between the mockup's stiffness and the air cylinder position. It was found experimentally that polynomials with larger degrees did not improve the results, while smaller degrees did not represent the system properly when compared to the variable stiffness estimation described in the next section. The

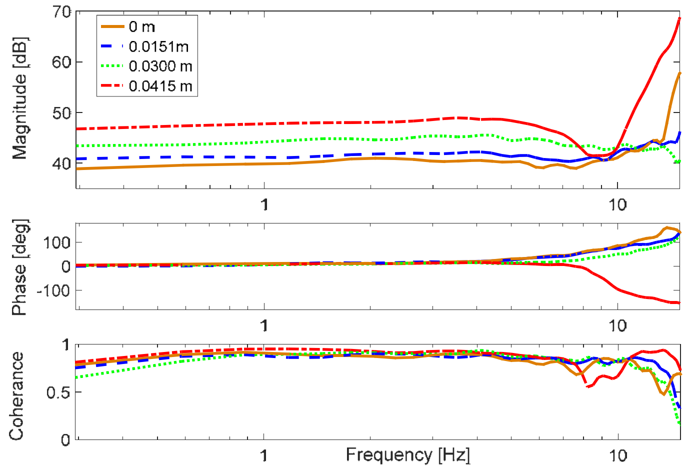

Fig.6: Impedance of the mockup at different air cylinder positions.

polynomial used to calculate the mockup's stiffness K as a function of actuator displacement d is:

$$K(d) = P_1 d^3 + P_2 d^2 + P_3 d + P_4 \tag{3}$$

where P_i (i=1, 2, 3, and 4) are the coefficients of the polynomial correlating the mockup's stiffness and the air cylinder position and were obtained using the Matlab® *polyfit* command.

TIME-VARYING STIFFNESS ESTIMATION

To test the ability of the Instrumented Walkway in estimating the stiffness of a time-varying system, the air cylinder was energized to reciprocate with a 2.2 Hz frequency and 0.11 m displacement. The vibrating platform was set with a square wave input using the maximum available torque and frequency of 1.61 Hz in the axis of rotation of the mockup where the variable stiffness could be modulated. The data was sampled at 300 Hz by the camera system, and the force plate sampled the reaction force at 7200 Hz (down-sampled to 300 Hz in post processing to match the camera system data). Based on the position of the foot and shin, ankle center of rotation, and the force plate reading, the ankle torques and angles were calculated. The ankle torques and angles were subdivided into blocks of 250 samples with 220 samples overlap.

A second order parametric model (equation 4) was used to identify the impedance parameters of the mockup correlating the angular displacements θ of the mockup and the applied torque τ on each data block similar to the method described by Rouse et al. [13]. In equation 4, J_{P+F} is the sum of the force plate and the mockup's ankle-foot inertias, b_F is the damping of the mockup, and k_F is the stiffness of the mockup. The angle derivatives were computed numerically in Matlab®.

$$\tau = \ddot{\theta} J_{P+F} + \dot{\theta} b_F + \theta k_F \tag{4}$$

Using equation 3, the estimated torques, and estimated angles, the stiffness of the mockup was calculated at each data block, resulting in the stiffness being estimated for every 100 ms window. The position of the air cylinder was measured during

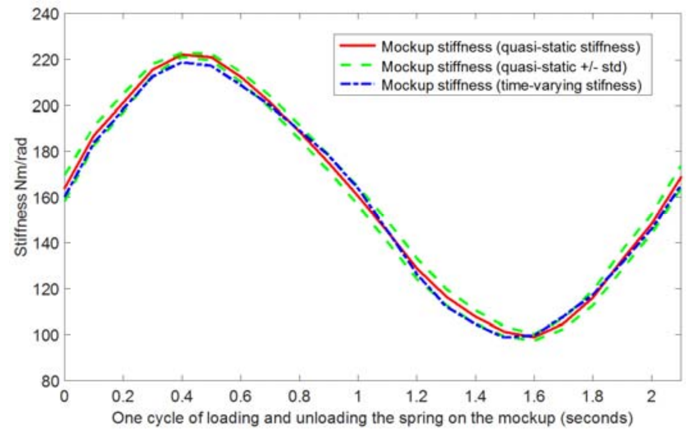

Fig. 7: Estimated mockup stiffness using different methods.

the experiments, and used as an input in the polynomial described by equation 2 to calculate the mockup's stiffness based on the air cylinder position. The stiffness based on the air cylinder position was also divided into blocks of 250 samples with 220 samples overlap and averaged for a representative stiffness at each block. Therefore, the stiffness was estimated using two independent methods and measurements simultaneously, one based on the measurement of the ankle's angles and torques, and one based on the measurement of the air cylinder position.

Each reciprocal motion of the cylinder was considered the equivalent of one step with varying stiffness from the lowest to highest value and back to the lowest stiffness, for a total of 66 cycles. The stiffness results from both methods were averaged across all the cycles. The results of the estimated mockup stiffness using the time-varying stiffness approach and the quasi-static stiffness approach can be seen in figure 7. The average damping b_F during the experiment was 0.82 ± 0.32 Nms/rad. The average inertia of the foot and force plate J_{P+F} was 0.046 ± 0.004 Nms^2/rad. The mockup foot inertia was calculated as 0.016 Nms^2/rad, resulting in an estimated force plate inertia of 0.030 Nms^2/rad.

DISCUSSION

The presented experiment showed the testing of a mechanism with mechanical properties similar to the human ankle and time-varying stiffness. The estimation of the mockup's stiffness using a stochastic method at constant stiffness value was used to calculate the mockup's stiffness based on the air cylinder position that controls the stiffness. The use of stochastic methods on the Instrumented Walkway has been shown to properly measure the stiffness of a system with constant dynamics [1]. This provides independent estimates of the mockup's stiffness allowing the comparison of the two methods during the same experiment, verifying the ability of the system to estimate time-varying dynamics using a method similar to what can be used during experiments on human subjects. Oscillation

The RMS error between the two methods was 2.81 Nm/rad (maximum 4.12 Nm/rad and minimum of -3.41 Nm/rad). The results showed that the proposed approach could estimate the stiffness of systems with time-varying impedance or constant impedance with similar accuracy. The damping of the mockup was low when compared to the stiffness with an average value of 0.82 ± 0.32 Nms/rad. A low damping is expected as the only damping in the mockup is due to the naturally occurring damping in the springs, frame, and spherical joint. Some variation in the damping is expected as the pre-load of the springs change the load on the spherical joint and may result in changes in damping. The inertia of the combined foot and force plate was 0.046 ± 0.004 Nms^2/rad. The low variation in inertia is expected since the inertia of the foot and force plate were constant during the experiments.

To balance the mockup, a spring rated at 3750 Nm was added in line with the shin above the weights. Therefore, if the mockup leans in any direction, this spring generates a torque, effectively balancing the mockup. This restoring torque is an unmeasured input to the system, potentially creating artifacts in the results. Unmeasured inputs have the characteristic of generating a drop in the coherence. Although a drop in the coherence is also associated with the presence of the natural frequencies, it is accompanied by a change in the magnitude and phase (as seen at around 8 Hz in figure 6, which is a natural frequency of the mockup). As it can be seen in figure 6, the balancing spring resulted in a drop in the coherence, but no changes in phase at frequencies below 0.6 Hz, and did not affect the results at higher frequencies.

CONCLUSIONS

In previous work, an Instrumented Walkway was designed and fabricated for the estimation of the ankle mechanical impedance during walking in arbitrary directions [1]. This Instrumented Walkway contains a powered vibrating platform so the users do not need to wear or carry any measurement device or actuation system except reflective markers used to record the ankle kinematics with a motion capture camera system. This paper described the continuous development of the Instrumented Walkway and presented a preliminary experimental validation of its capability to estimate the time-varying impedance of a system. A mockup with mechanical characteristics similar to a human lower leg and controllable time-varying stiffness was fabricated. The stiffness of the mockup was estimated with fixed and time-varying stiffness. With fixed stiffness, stochastic system identification methods were used to estimate the mockup's impedance. A second order parametric model was used to estimate the mockup's stiffness when the mockup presented time-varying stiffness. The RMS error between the two methods was 2.81 Nm/rad (maximum 4.12 Nm/rad and minimum of -3.41 Nm/rad). The results showed that the proposed approach can estimate the stiffness of systems with time-varying dynamics or static dynamics with similar accuracy.

FUTURE WORK

The main goal of developing the Instrumented Walkway was to estimate the mechanical impedance of the human ankle during walking in arbitrary directions. Future work will first focus on improving the design and evaluating the capability of the system to estimate the impedance of a mockup with time-varying stiffness and relative angular displacement of the shin with respect to the foot, as it is occurs in the human lower leg during walk. With successful evaluation under these conditions, the Instrumented Walkway can be used for estimation of the human ankle impedance during different types of gait. The types of gait can be extended but are not limited to turning maneuvers, walking on different ground profiles, walking with different gait speeds, walking while carrying loads, climbing/descending slopes, and traversing slopes.

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