Identification of human joint impedance using a wearable powered knee exoskeleton

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Introduction

Joint impedance is the mechanical property that describes the dynamical relationship between joint angle and torque. It provides a description of the neuromechanical behavior of a joint and it is regulated according to the surrounding environment to promote a stable interaction with it. Joint impedance has been shown to be successfully estimated using system identification techniques on humans experimentally[1].

Estimation of joint impedance is critical in post-stroke individuals particularly when they are in the chronic state of the pathology (after six months from onset). After this time, the affected limbs commonly show signs of increased resistance to movements. This condition of altered joint impedance is clinically described as joint hyper-resistance[2]. The presence of hyper-resistance provokes pain, restricts the range of motion of the affected joints, limits the achievement of functional tasks, and might lead to health complications, not including worsening of the quality of life.

Joint hyper-resistance can have both mechanical and neural causes. Neural causes include muscular spasticity and increased background activation among others, while a mechanical cause is contracture. Specific treatments are dependent on the origin of the impairment, but there is still limited knowledge on the pathophysiology of joint hyper-resistance, and, moreover, current diagnostic tools are only qualitative.

Currently, the evaluation of hyper-resistance is performed by clinicians using manual perturbations. The relationship between the applied constant-speed angular perturbations and the corresponding perceived joint reaction torque (i.e., joint resistance) is attributed solely to contracture for slow perturbations, while it is attributed to both contracture and spasticity for faster movements. The perceived resistance is then translated to a numeric value by the clinician to assess the severity of the impairment. Common metrics include the Tardieu scale[3] and the (Modified) Ashworth Scale, (M)AS[4]. Both scores are highly dependent on the clinician's perception and experience and provide only a qualitative estimation of the level of spasticity[3].

To address these issues and limitations, we propose a quantitative approach based on measured joint torque in response to an externally applied joint motion using a motorized and controlled apparatus to perform the constant speed perturbation similarly to the clinical evaluation. Such an approach can provide a quantitative and objective estimate of joint resistance. System identification methods can be used to analyze the measured input-output signals (angular position and joint reaction torque) and build a quantitative model of the joint impedance. System identification methods applied to humans have successfully shown to be a viable approach to gain more insight about the joint properties up to how humans perform sensorimotor integration during balance[1,5,6,7]. However, one of the drawbacks of these studies is that they require expensive and bulky custom designed actuated devices which are solely used for tailored system identification experiments. Recent studies have shown the potential of using wearable actuated devices as alternative perturbation devices[8,9].

In this work we further investigated the viability and usability of a wearable and lightweight powered knee exoskeleton as a perturbation device for estimating knee joint impedance. This work leads the way to develop a reproducible protocol to quantitatively estimate human joint impedance, particularly in chronic post-stroke individuals. The proposed method can provide insightful indications of the underlying neuromuscular causes contributing to the hyper-resistance (passive, reflexive, and co-contraction). Preliminary results from a pilot testing are presented.

Materials and Methods

Five healthy adult subjects (three female) (age±1SD: 31±7 [yr]) were recruited and screened to ensure no presence of known neurological, sensory, or muscular problems. Data from the male subjects were excluded because of technical issues that affected the quality of the recordings. The mean anthropometric characteristics of the remaining subjects were: height (169±9 [cm]) and weight (65±18 [kg]).

Subjects participated in a 90-min session including informed consenting, anthropometric measurements, preparation for sEMG recordings, fitting of the exoskeleton to the subject's leg and the perturbation trials.

All subjects were seated during the data collection. A custom setup was developed to allow relaxation of the muscles responsible for knee flexion and extension (see Fig. 1A). Position perturbations to the knee joint were applied using a wearable actuator (Fig. 1A and 1B).

Different profiles for the perturbations were tested, including i) constant-speed and ii) small-amplitude perturbations. The order of the testing conditions was randomized across subjects. To prevent fatigue and ensure comfort, resting was allowed between trials.

In this work preliminary results from the constant-speed trials are presented. The perturbation consisted of a ramp&hold movement at constant velocity. Two angular velocities were used: 5 and 20 deg/s, referred to as "SLOW" and "FAST", respectively.

Joint angular position was obtained by an encoder embedded in the exoskeleton system. Knee flexion of 90 deg and full extension corresponded to a reading of 90 deg and 180 deg, respectively. Knee joint resistance torque was measured using a load cell calibrated to return knee torque in response to applied joint motion.

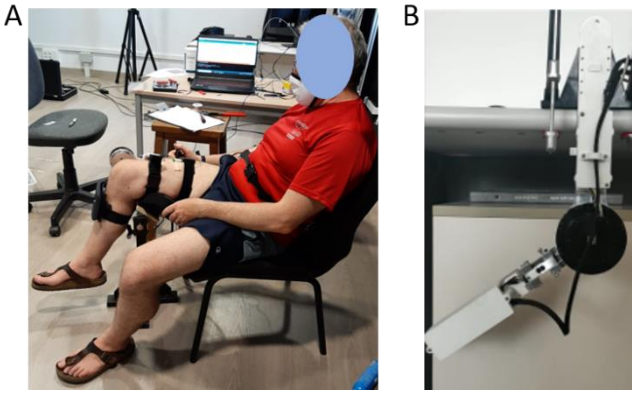

Figure 1: A. A subject seated during the experiments. B. Actuation system of the wearable knee exoskeleton

The data were downsampled to 100 Hz, sensor spikes artifacts were removed and the contribution of the weight of the exoskeleton on the torque signal was removed. The data were divided into ramp (dynamic) and hold (static) segments. The data from the static segments were used to estimate the weight of the shank and foot. For each ramp segment and each direction of motion (extension and flexion) the ratio between the measured torque and the knee joint angle was used to estimate the knee joint stiffness.

Results

The human leg for the healthy subjects included in the study showed a fairly linear behavior in response to the constant-speed perturbations (see Fig. 2). Torque increased as the joint angle increased because of the added contribution of gravity as the leg became more extended (i.e. shank close to horizontal orientation).

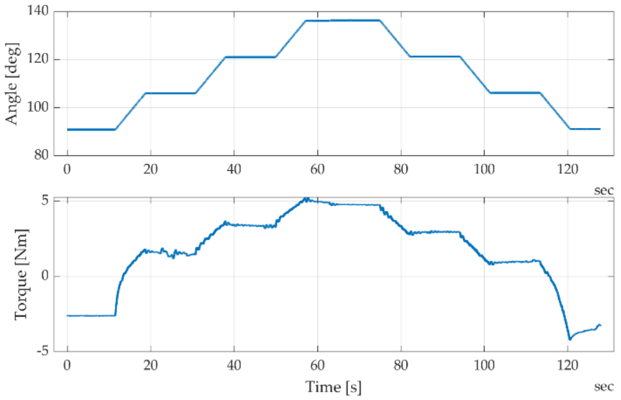

Figure 2: Sample data from one subject for a "SLOW" trial.

A sample of torque values plotted versus joint angle is shown in Fig. 3A. Note that for more flexed joint angle configurations (pink and light-blue color data in Fig. 3A), the torque-angle relation is less linear.

The values of the estimated stiffness appear to be the same independently of the direction of motion (flexion/extension) at least for more extended configurations of the leg (angles above 120 deg) as shown in Fig. 3B. Additionally, what is evident from the data shown in Fig. 3B and less evident in the joint torque-angle relationship (Fig. 3A) is that the stiffness is angle dependent and it appears to increase with the amount of knee flexion.

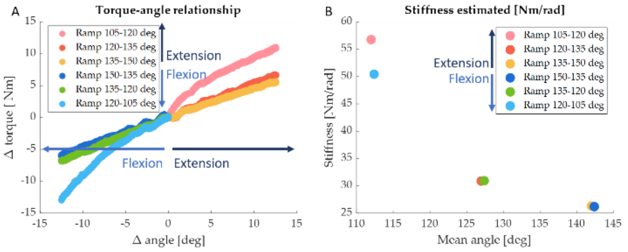

Figure 3: Sample data from a subject. A. Knee torque-angle relationship. B. Estimated stiffness

Discussion and Conclusion

In this work we have set forth to develop and test the viability of a wearable powered knee exoskeleton to estimate the knee joint impedance. The motivation was to develop a method for a more objective and quantitative estimation of joint resistance as opposed to clinical practice. A simplified joint impedance model was used to analyze the ramp-and-hold data, proving an intuitive and accessible method for the estimation of joint stiffness during conditions mimicking clinical settings. The estimate shows promising results, capable of suggesting that stiffness of the knee joint changes at different angular positions.

The preliminary findings from this work support the viability of such an approach to obtain a quantitative estimate of joint resistance. Additionally, the analysis of the small-amplitude data is expected to provide a more dynamically relevant model, providing enough information to analyze the impedance over a wide range of frequencies. As last remark, further work including more subjects and chronic stroke sufferers is needed to investigate the viability of this method with such individuals.

Funding

The project leading to these results has received funding from the European Union's Horizon 2020 research and innovation programme under Marie Skłodowska-Curie grant agreement No.801342 (Tecniospring INDUSTRY) and the Government of Catalonia's Agency for Business Competitiveness (ACCIÓ) and from the Research Foundation Flanders (FWO-Vlaanderen, PhD Fellowship No. 1182019N), the Flemish.

Acknowledgments

We thank M.R. Epke and J. de Miguel Fernández for their assistance with the development of the system.

References

[1] Cavallo G. *et al.*, Conf. Proc. IEEE Eng. Med. Biol. Soc. EMBC, 4835-8, 2020, 2020
[2] van den Noort, J. C. *et al.*, Eur. J. Neurol., 24:981-e38, 2017
[3] Alibiglou L. *et al.*, J Neuroeng Rehabil, 5, 18:1-14, 2008
[4] Shorter A.L. *et al.*, IEEE ICORR, 246-51, 2019
[5] Cenciarini M. *et al.*, IEEE TBME, 57(2):267-75, 2010
[6] Cenciarini M., Peterka R.J., JNP, 95(5):2733-50, 2006
[7] van der Helm C.T. *et al.*, J. Neurosci. Methods, 119(1):1-14, 2002
[8] Tucker M.R. *et al.*, IEEE TBME, 64(10):2331-43, 2017
[9] Nazon Y. *et al.*, J. Biomech. Eng., 21 Jul. 2021 Epub