Evaluation of Motion/Force Transmission Between Passive/Active Orthosis and Subject Through Forward Dynamic Analysis

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Abstract Forward dynamic analysis of the acquired gait of subjects assisted by either passive or active knee-ankle-foot orthoses and crutches is used to evaluate the motion and force transmission between orthosis and subject depending on the connecting stiffness. Unlike inverse dynamic analysis, this approach allows to consider the subject's limbs and the assistive devices as different entities, so that their relative behavior may be studied. The quality of motion transmission and the intensity of interface forces are evaluated for a range of connecting stiffness values, so that those providing the best trade-off between both aspects can be identified.

1 Introduction

The analysis of acquired gait motion through forward dynamics instead of traditional inverse dynamics offers some advantages, such as superior dynamic consistency [1], ability to consider muscle activation/contraction dynamics [2], and feasible computation of contact forces between subject and assistive devices [3]. The present work focuses on this last topic.

Some contributions can be found in the literature addressing the problem of evaluating the interaction between exoskeleton and subject by modeling each entity separately. Indeed, the characteristics of the connecting elements are essential for two main reasons: (i) to achieve a good motion transmission between the device and the limb to yield a suitable gait; (ii) to keep the contact pressures below an

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admissible threshold to avoid skin wounds. A planar model of a human wearing ankle-foot orthoses is presented in [3], where the model coordinates are kinematically guided with exception of the subject's ankle rotations, which can move freely, thus simulating a total absence of muscular action. A three-dimensional model of a human assisted by a hip-knee-ankle-foot exoskeleton is proposed in [4], the motion prediction problem being addressed by optimal control techniques (optimization).

Unlike the methods used in the previous references, the present work carries out a forward dynamic analysis of the acquired motion, which can be considered more dynamically consistent than the almost full kinematic guidance of [3], and much less involved and computationally expensive than the optimal control technique presented in [4].

2 Materials and Methods

2.1 Experiments and Models

In the first case, the subject was an adult female of mass 65 kg and height 1.52 m with spinal cord injury at T11. In the experiment, she was wearing a pair of passive knee-ankle-foot orthoses while walking over two embedded force plates with the help of two instrumented crutches [5]. Her motion was captured by 12 optical infrared cameras that computed the position of 43 optical markers, as illustrated in Fig. 1.

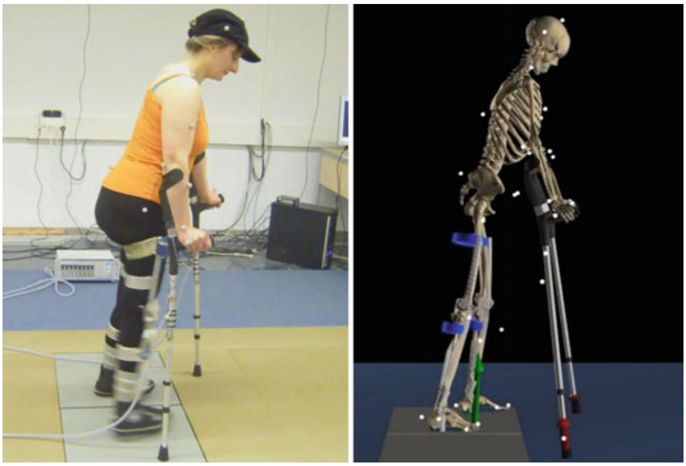

Fig. 1 Gait of spinal cord injured subject assisted by passive orthoses and crutches: acquired motion and computational model

The human 3D model consists of 18 anatomical segments: pelvis, torso, neck, head, and two hindfeet, forefeet, shanks, thighs, arms, forearms and hands with the crutches rigidly connected to them. The segments are linked by ideal spherical joints, thus defining a model with 57° of freedom (6 of the base body plus 51 of the joints). A force model is used for foot-ground and crutch-ground contacts. The orthosis model has two links, the lower link connected to the subject's ankle by a revolute joint, and the upper link connected to the lower link by another revolute joint at knee level, so that each orthosis adds two degrees of freedom. Moreover, torsional spring-damper elements are included in the revolute joints at knee and ankle levels, reproducing the locking and anti-foot-drop mechanisms, respectively. The limb/orthosis connecting elements are modeled by linear spring-dampers linking points of the limb and the orthosis, both at hip and knee levels.

In the second case, the subject was a healthy male of mass 74 kg and height 1.60 m. This time the orthoses were active, featuring an electric motor at knee level able to provide a controlled torque to yield normal gait. Therefore, the only orthosis modeling difference with the first case is that the torsional spring-damper at knee level is substituted by a variable torque obtained from the same control algorithm implemented in the actual motor driver.

2.2 Formulation

The forward dynamic analysis of the acquired motion was carried out by means of the formulation in minimum number of coordinates proposed in [6] and called matrix-R, along with a version of the computed torque control method for under-actuated systems [7] that provided the inputs required by the system to track the acquired motion.

In both cases, the inputs were applied to all the joints of the human model, i.e. 51. In the first case (injured subject), inputs at knees and ankles accounted for passive torques in such joints suffering from absence of muscular activity. In the second case (healthy subject), the subject was able to provide torque at knee and ankle levels too. The outputs to be tracked were, in both cases, the histories of the 57° of freedom of the human model.

2.3 Tests

In each case, forward dynamic simulations were run for the three different stiffness values of the orthosis/limb connecting elements gathered in Table 1. The corresponding damping values were obtained by imposing critical conditions.

Table 1 Stiffness of orthosis/limb connecting elements

k (N/m)	Case 1 (passive)			Case 2 (active)		
	A	B	C	A	B	C
Hip	1e3	1.5e3	2e3	1e3	1.5e3	2e3
Knee	1e4	2e4	8e4	1e4	2e4	8e4

3 Results

To evaluate in each case the orthosis/limb relative motion and force transmission achieved for the different stiffness values assigned, plots (Fig. 2) have been generated showing the misalignment and the reaction force at knee level, since both magnitudes were always less critical at the hip.

4 Discussion

In the first case, higher values of the connecting stiffness provide a better motion transmission at the cost of higher maximum reaction forces, although little difference is observed in the forces for the three stiffness values compared. Moreover, it can be seen that, as it could be expected, lower demand is produced during the short swing phase than during the long stance phase.

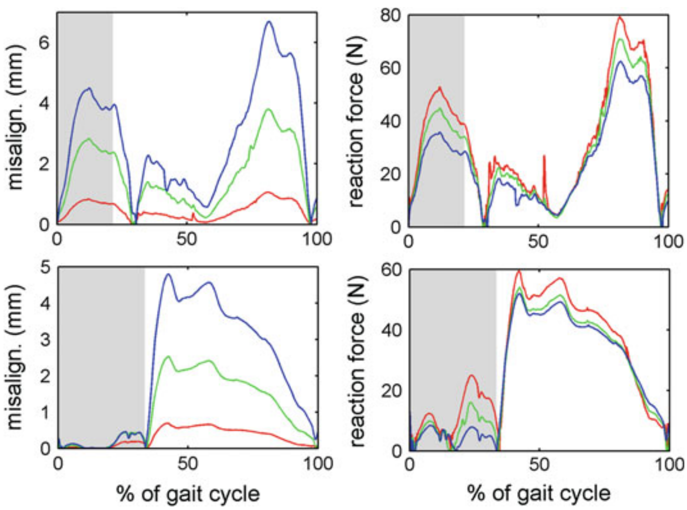

Fig. 2 Orthosis/limb misalignment (*left*) and reaction force (*right*) in the right leg at knee level for low (*A*, *blue*), medium (*B*, *green*) and high (*C*, *red*) values of the stiffness of the connecting elements, for case 1 (*top*) and case 2 (*bottom*). The *grey* area represents the swing phase

In the second case, again there is a better motion transmission for higher stiffness values, the reaction forces showing similar values for the three tested stiffnesses. Furthermore, relevant misalignments and reaction forces are obtained mainly during the stance phase, a fact that can be explained by the active character of orthosis and healthy subject, likely fighting against each other along that phase.

5 Conclusions

It has been shown that the forward dynamic analysis of the acquired motion allows to evaluate the motion/force transmission between orthosis and subject's limb in a way that is more dynamically consistent than kinematic guidance and more simple and efficient than optimal control.

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References

1. J.A.C. Ambrosio, A. Kecskemethy, Multibody dynamics of biomechanical models for human motion via optimization, in *Multibody Dynamics—Computational Methods and Applications*, ed. by J.C. Garcia Orden, J.M. Goicolea, J. Cuadrado (Springer, Dordrecht, 2007), pp. 245–270
2. D.G. Thelen, F.C. Anderson, Using computed muscle control to generate forward dynamic simulations of human walking from experimental data. J. Biomech. **39**, 1107–1115 (2006)
3. P.C. Silva, M.T. Silva, J.M. Martins, Evaluation of the contact forces developed in the lower limb/orthosis interface for comfort design. Multibody Sys.Dyn. **24**(3), 367–388 (2010)
4. K.H. Koch, K. Mombaur, ExoOpt—a tool for evaluating exoskeleton designs using model-based optimization, in *Proceedings of International Workshop on Wearable Robotics*, Bayona, Spain, Sep. 2014
5. U. Lugris, J. Carlin, A. Luaces, J. Cuadrado, Gait analysis system for spinal cord-injured subjects assisted by active orthoses and crutches. J. Multi-body Dyn. **227**(4), 363–374 (2013)
6. J. Garcia de Jalon, E. Bayo, Kinematic and Dynamic Simulation of Multibody Systems (Springer, New York, 1994). Chapter 5
7. F. Mouzo, U. Lugris, R. Pamies-Vila, J.M. Font-Llagunes, J. Cuadrado, Underactuated approach for the control-based forward dynamic analysis of acquired gait motions, in *Proceedings of ECCOMAS Thematic Conference on Multibody Dynamics 2015*, Barcelona, Spain, Jun–Jul 2015