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Validation of a Marker Model for Gait Analysis with Wearable Exoskeletons

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Abstract: The aim of the present study was to develop and validate a new marker model for optoelectronic systems adapted to wearable devices, in order to have an analysis tool for kinematic gait evaluation of reproduced patterns by exoskeletons. The marker model has a total of 36 retro-reflective markers attached bilaterally to anatomical landmarks during the static measures (without exoskeleton) and 28 markers at the dynamics measures (with exoskeleton). The main difference between others kinematic models and the described adapted model was the placement of the three markers in the back thigh and the other three in the back calf, what allowed removing the hip, thigh, knee, tibia and ankle markers. The proposed adapted marker model could be an effective tool to validate the joint movement and velocities of those wearable exoskeletons that at present have been developing.

Key words: Optoelectronic system, adapted model, gait analysis.

1. Introduction

Rehabilitation and functional compensation of gait is an active field of application for exoskeleton since the last fifteen years [1]. Robotic devices have been focus on improving mobility and autonomy of patients, providing longer gait training sessions and reducing the physical effort of therapists compared to manually assisted training [2, 3]. Those wearable devices attempt to reproduce humanlike kinematic gait patterns in an energy-efficient manner for a better acceptance and usability. But it is necessary to evaluate how humanlike are those patterns and if they are appropriated for rehabilitation and functional compensation of gait.

The gait and motion analysis, as an effective functional outcome measure traditionally used to clinical evaluations before orthopaedic surgeons and rehabilitation [4, 5], could be an effective tool to evaluate and validate those gait patterns that wearable exoskeletons reproduce. Currently, the most of gait laboratories carry out the analysis with 3D motion capture optoelectronic systems that require retro-reflective markers attached to anatomical landmarks, principally of the pelvis, hip, knee, ankle and foot. Those anatomical points are mostly hidden by the exoskeletons what prevent from analyse gait patterns wearing them.

The aim of the present study was to develop and validate a new marker model for optoelectronic systems adapted to wearable devices, in order to have an analysis tool for kinematic gait evaluation of reproduced patterns by exoskeletons.

2. Material and Methods

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The validation of the marker model was carried out with the hybrid system developed by the Spanish National Research Council. Hybrid system joins together a wearable exoskeleton robot with hip, knee and ankle control and a smart robotic walker which provides stability in dynamic and static conditions with body weight supported. The exoskeleton is height adjustable from 150 to 190 cm tall and it perfectly attach to the body subject with eight clamps. The smart robotic walker has two free rear wheels and two tractor

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front wheels. Two elevating arms, placed on a superior plane, elevate the user by means of a chest harness. Hybrid system performed joint's kinematic low speed gait at 0.25 m/s, which was previously recorded from healthy subjects.

The gait analysis was performed in the Biomechanics Laboratory of the Faculty of Physical Activity and Sport Sciences at the Technical University of Madrid. A Vicon 3D motion capture optoelectronic system (Oxford Metrics, Oxford, UK) captured the gait cycles with six cameras located along a 10-m walkway and sampling at 120 Hz. The experimental space was dynamically and statically calibrated with an error of less than 2 cm and a static reproducibility of 0.4%.

One subject was measured with the wearable exoskeleton reproducing the gait pattern of a low walking speed (0.25 m/s). One static and three dynamic trials, which included a right and left gait cycle, were recorded. Kinematic parameters were obtained from an average of three cycles of each side and standardized to 0-100% of a gait cycle. The data of the dynamic trials were also acquired in real time by the inertial sensors of the wearable exoskeleton which provided the position and angle of the hip, knee and ankle in sagittal plane (flexion and extension).

2.2 Placement Markers Model

During the static measures (without exoskeleton), a total of 36 retro-reflective markers were attached bilaterally to anatomical landmarks (right (R) and left (L)) following an adapted model from Vicon's kinematics model (Fig. 1): on calcaneous (LHEE and RHEE), second metatarsal head (LTOE and RTOE), lateral malleolus along the transmalleolar axis of the ankle (LANK and RANK), medial malleolus along the transmalleolar axis of the ankle (LANK2 and RANK2), lower lateral 1/3 of the shank (LTIB and RTIB), lateral epycondile of the knee (LKNE and RKNE), medial epycondile of the knee (LKNE2 and RKNE2), lower lateral 1/3 of the thigh (LTHI and RTHI), anterior superior iliac spine (LASI and RASI), posterior superior iliac spine (LPSI and RPSI) and over the grater trochanter (LTROC and RTROC). There were also attached three markers over the back side of the thigh (LMUS1, LMUS2, LMUS3 and RMUS1, RMUS2, RMUS3) and calf (LGEM1, LGEM2, LGEM3 and RGEM1, RGEM2, RGEM3).

The four markers placed in the pelvis (LASI, RASI, LPSI and RPSI) defined the hip joint centre location. The knee joint centre and the ankle joint centre were determined by the midpoint between the medial and lateral markers of each joint (medial and lateral epicondyles (KNE2-KNE) and medial and lateral malleoli (ANK2-ANK), respectively). The distance between the marker placed at the greater TROC (trochanter) of the femur and the floor defined the leg length.

The three markers of the back thigh (MUS1, MUS2 and MUS3) remembered and redefined the hip joint centre location and movement and the other three markers of the back calf (GEM1, GEM2 and GEM3) redefined the knee and ankle joint centres during the dynamics measures.

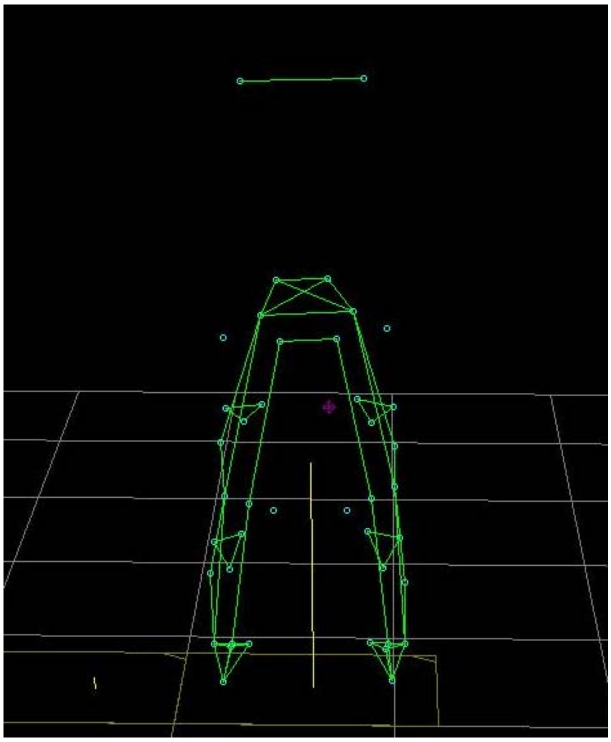

Fig. 1 Adapted marker placement model (static).

The dynamic markers placement model has 28 retro-reflective markers (with the wearable exoskeleton) (Fig. 2). There were removed some of the markers from the subject's body: the markers placed at the trochanters (RTROC and LTROC), the markers in the midpoint of thighs and calves (RTHI, LTHI, RTIB and LTIB) and the medial and lateral markers of the knees and ankles (RKNE, RKNE2, LKNE, LNKE2, RANK, RANK2, LANK and LANK2). There were added six new markers to the center of the six engines to control the exoskeleton position (E_LHIP, E_LKNE, E_LANK y E_RHIP, E_RKNE, E_RANK).

The four markers attached to the Pelvis (LASI, RASI, LPSI and RPSI) measured the pelvic tilt, pelvic obliquity and pelvic rotation movements. The heel and toe markers were used to define the heel contact and foot off to determine the beginning and the end of each gait cycle.

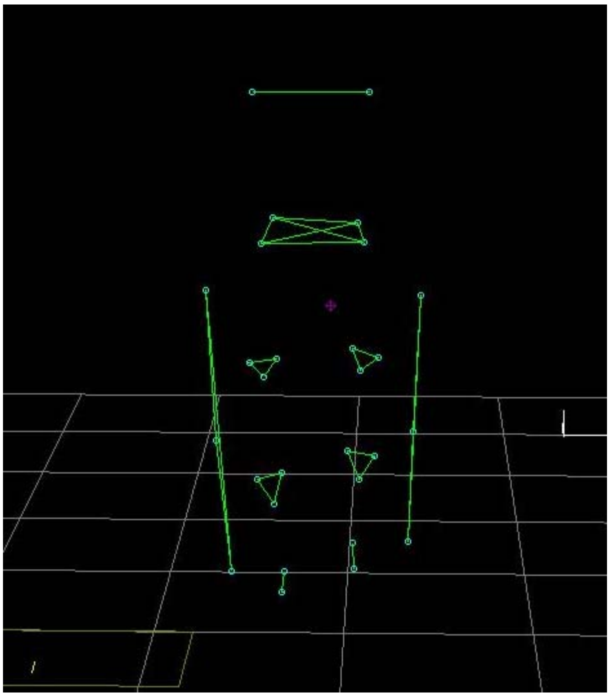

Fig. 2 Adapted marker placement model (dynamic).

3. Results

There were compared the movements in sagittal plane (flexion and extension movements) of hip, knee and ankle joints, between the gait pattern previously recorded from healthy subjects and reproduced by the exoskeleton (gait pattern), the gait pattern recorded by the inertial sensors of hybrid system (hybrid) and the gait pattern captured by the 3D motion capture optoelectronic Vicon system (Vicon system). Discrete data of flexion and extension movements were identified from the kinematic curves. Maximal flexion, minimal flexion (maximal extension) and flexion at initial contact of the heel (0% of the gait cycle) were studied.

The statistical analysis was carried out using SPSS v.21 software (SPSS Inc., Chicago, IL, United States). Means and standard deviations (Mean ± SD) were calculated, and a non-parametrical Kruskal-Wallis test was used. The alpha level of significance was set at 0.05 for all statistical tests.

The results showed that there were no significant differences between the original gait pattern reproduced by the exoskeleton and the Hybrid and Vicon system recordings ($p > 0.05$). Table 1 shows discrete data of the kinematic curves of the hip, knee and ankle in sagittal plane. There were no significant differences in the position of the hip, knee and ankle at the IC (initial contact) of the heel ($p > 0.05$). There were also no significant differences at the maximal and minimal flexion (maximal extension) of the hip, knee and ankle between the three patterns ($p > 0.05$).

4. Discussions and Conclusions

The aim of the present study was to develop and validate an adapted marker model for optoelectronic systems useful for kinematic gait evaluation of wearable exoskeletons. As it was shown in the results, the adapted marker model that we described was as reliable as the Vicon's kinematic model for normal gait analysis. The main difference between Vicon's kinematic model and the described adapted model was the placement of the three markers in the back thigh (MUS1, MUS2 and MUS3) and the other three in the back calf (GEM1, GEM2 and GEM3), what allowed removing the hip, thigh, knee, tibia and ankle markers.

Table 1 Comparison of gait pattern, hybrid pattern and Vicon system pattern.

Events	Gait pattern	Hybrid	Vicon system
Hip flexion at IC (°)	33.30	32.38 ± 2.01	33.86 ± 1.30
Hip maximal flexion (°)	36.72	35.21 ± 0.12	36.50 ± 4.52
Hip minimal flexion (°)	4.12	5.67 ± 0.04	4.05 ± 3.11
Knee flexion at IC (°)	14.16	15.94 ± 0.15	16.38 ± 4.40
Knee maximal flexion (°)	57.83	58.45 ± 1.13	57.79 ± 5.65
Knee minimal flexion (°)	12.36	10.58 ± 0.31	10.36 ± 1.72
Ankle flexion at IC (°)	5.85	5.00 ± 0.34	5.76 ± 2.43
Ankle maximal flexion (°)	16.85	15.27 ± 0.21	16.06 ± 3.79
Ankle minimal flexion (°)	-9.34	-7.42 ± 0.17	-6.13 ± 0.17

(Mean ± standard deviations) ($p > 0.05$)

Other researchers have developed new protocols and marker models for gait analysis [6-9], but none of them could be used with wearable exoskeletons because most of the markers would be placed under the exoskeleton. This would make impossible to capture the kinematic gait movement with the optoelectronic cameras, considering that it is necessary that more than two cameras record at the same time every marker position to reconstruct the three dimensional movement trajectories. The proposed adapted marker model could be an effective tool to evaluate the joint movement and velocities of those wearable exoskeletons that at present have been developing. Those validations would better adapt the wearable devices to the users' anatomy and biomechanics, what may improve rehabilitation programs and health-related quality of life of patients.

References

[1] Ama, A. J., Koutsou, A. D., Moreno, J. C., Reyes, A., Agudo, A. G., and Pons, J. L. 2012. "Review of Hybrid Exoskeletons to Restore Gait Following Spinal Cord Injury." *J. Rehabil. Res.* 49 (2): 497-514.

[2] Wirz, M., Bastiaenen, C., Bie, R., and Dietz, V. 2011. "Effectiveness of Automated Locomotor Training in Patients with Acute Incomplete Spinal Cord Injury: A Randomized Controlled Multicenter Trial." *BMC Neurology* 11: 60-4.

[3] Swinnen, E., Duerinck, S., Baeyens, J. P., Meeusen, R., and Kerckhofs, E. 2010. "Effectiveness of Robot-Assisted Gait Training in Persons with Spinal Cord Injury: A Systematic Review." *J. Rehabil. Med.* 42: 520-6.

[4] Theologis, T. 2009. "Gait and Clinical Movement Analysis Research Priorities: 2007 Update from Research Committee of the Gait and Clinical Movement Analysis Society." *Gait Posture* 29: 169-71.

[5] Chambers, H. G., and Sutherland, D. H. 2002. "A Practical Guide to Gait Analysis." *J. Am. Acad. Orthop. Surg.* 10: 222-31.

[6] Ferrari, A., Benedetti, M. G., Pavan, E., Frigo, C., Bettinelli, D., Rabuffetti, M., Crenna, P., and Leardini, A. 2008. "Quantitative Comparison of Five Current Protocols in Gait Analysis." *Gait Posture* 28: 207-16.

[7] Leardini, A., Sawacha, Z., Paolini, G., Ingrosso, S., Nativo, R., and Benedetti, M. G. 2007. "A New Anatomically Based Protocol for Gait Analysis in Children." *Gait Posture* 26: 560-71.

[8] Collins, T. D., Ghoussayni, S. N., Ewins, D. J., and Kent, J. A. 2009. "A Six Degrees-of-Freedom Marker Set for Gait Analysis: Repeatability and Comparison with a Modified Helen Hayes Set." *Gait Posture* 30: 173-80.

[9] Manca, M., Leardini, A., Cavazza, S., Ferraresi, G., Marchi, P., Zanaga, E., and Benedetti, M. G. 2010. "Repeatability of a New Protocol for Gait Analysis in Adult Subjects." *Gait Posture* 30: 282-4.