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AN AMBULATORY SYSTEM FOR KINEMATIC AND KINETIC ANALYSIS OF GAIT

[1] Hossein Rouhani, [1]Julien Favre, [2]Xavier Crevoisier, [2]Swati Chopra and [1]Kamiar Aminian
[1]Laboratory of Movement Analysis and Measurement, Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland
[2]Department of Orthopaedic Surgery and Traumatology, Centre Hospitalier Universitaire Vaudois and University of Lausanne (CHUV), Switzerland; email: hossein.rouhani@epfl.ch, web: lmam.epfl.ch

SUMMARY

In the present work, we introduced an ambulatory system for both kinematics and kinetics assessment of ankle and foot joints during long-term gait. This system consisted of an integration of plantar pressure insoles and several modules of inertial sensors. Our whole body-fixed sensor package could measure spatio-temporal parameters of gait, 3D joint angles, joint moments, joint power, ground reaction force, and plantar pressure distribution. First, we compared the kinematic and kinetic parameters obtained by this ambulatory system to those obtained by an optoelectronic motion capture system and a force-plate in a gait laboratory. Second, we showed that the measured parameters by this system could i) distinguish populations with foot and ankle pathologies from healthy population, ii) assess the improvements in the patients' gait after surgical treatments, iii) compare different surgical techniques based on gait outcomes. Our proposed ambulatory system could assess kinematics and kinetics of ankle and foot joints as well as their variation during long-term gait (several 100-meters). Its convenient use for both clinicians and patients in clinical routines has been evaluated for over 100, mainly elderly, patients with orthopaedic conditions. In conclusion, this system is suggested for a variety of assessments in clinical routines.

INTRODUCTION

Instrumented gait analysis has been used a variety of clinical disciplines for objective evaluation of a pathology or a treatment. The kinematics and kinetics of human body during gait has usually been assessed in a gait laboratory using stationary motion capture systems. However, ambulatory systems for gait analysis might be preferred since i) they can measure more natural gait in daily life, ii) they can measure variability of gait in several consecutive gait cycles, and iii) their use is convenient for clinical routines [1,2]. In past, we introduced ambulatory measurement systems for spatio-temporal parameters of gait and lower limb joint angles [1,2]. However, an ambulatory system to measure both kinematics and kinetics of lower limbs joints, in particular ankle and foot joints, has not been developed and evaluated for clinical evaluations.

This present work aimed to introduce an ambulatory system for measurement of foot and ankle kinematics and kinetics during long-term gait. In this work, foot and ankle kinematics and kinetics estimation using this ambulatory system have been validated against standard gait lab systems, and suitability of their use for clinical evaluations have been investigated.

METHODS

a) Measurement system

Our ambulatory measurement system (Figure 1) consisted of an integration of i) five modules of inertial sensors (3D Gyroscope + 3D Accelerometer) connected to portable data-loggers (Physilog, CH) all weighed <400 gr, and ii) plantar pressure insoles and its portable data-logger (Novel, DE) all weighed <1200 gr, both recorded synchronously at 200 Hz.

Figure 1. The ambulatory system with a sensor configuration for ankle and foot joints assessment.

b) Measured parameters

Following parameters were measured using the ambulatory system in long-term gait outside gait lab. The algorithms for each measurement are described in the references (Figure 2).

1- <u>3D joint angles:</u> metatarso-phalangeal (MPJ), midtalar, and ankle [2,3]
2- <u>3D angular velocity of segments:</u> hallux, forefoot, hindfoot, and shank [2,3]
3- <u>3D ground reaction forces (GRF)</u>: Anterior-Posterior, Medial-Lateral, Vertical [4]
4- <u>Joint moments & power:</u> MPJ, midtalar, and ankle [5]
5- <u>Plantar pressure distribution parameters:</u> peak pressure, maximum force, their occurrence instants, and contact time in 10 foot sub-regions: medial+lateral hindfoot, medial+lateral midfoot, medial+central+lateral forefoot, and $1^{st}+2^{nd}+3^{rd}\sim5^{th}$ toes [6]
6- <u>Spatio-temporal parameters of gait:</u> cadence, double support, limp, stride length, speed, stance time [1,7]
7- <u>Inter-stride variability of parameters 1~6 in long-term gait</u>

c) Technical Validity of the measured parameters

The accuracy of the above-mentioned measured parameters was validated through comparison with those obtained by stationary systems in a gait lab [3-5]. For this purpose, each subject wore sandals imbedding the body-fixed sensors, and walked over the force-plate (Kistler, CH), surrounded by seven motion-capture cameras (Vicon, UK) over 12 times where the ambulatory and stationary systems recorded synchronously. Parameters 1~4 were measured by both systems and were then compared together.

d) Clinical Protocol

15 individuals with ankle osteoarthritis, 11 individuals treated by total ankle replacement surgery, 9 individuals treated by ankle arthrodesis surgery, and 10 age-matched controls were involved. Subject wore the ambulatory system (Figure 1) and walked twice 50-meters in a hospital corridor. Parameters 1~7 were calculated and compared among populations using Wilcoxon rank-sum test. Besides, the correlations between these parameters and the established clinical scores (FFI and AOFAS ankle-hindfoot) were calculated to investigate their convergent validity.

RESULTS AND DISCUSSION

MPJ, midtalar, and ankle joints angles in the sagittal, coronal, and transverse plane measured by the ambulatory system had root-mean-square (RMS) difference of 1 degree (on average) compared to those measured by Vicon cameras [3]. Anterior-posterior, medial-lateral, and vertical ground reaction forces had RMS difference of 7%, 12%, and 4% of the measured range with those measured by force-plate [4]. Ankle joint moments in the sagittal and transverse planes and ankle power showed RMS difference of 9%, 23%, and 20% with those measured by cameras and force-plate [5].

Several kinematic parameters (joint angle ranges and segment angular velocity peaks) in 50-meter walking were significantly ($p<0.05$) different between ankle osteoarthritis patients and controls. These differences were no more significant after total ankle replacement surgery and were still significant after ankle arthrodesis surgery [8]. Several kinetic parameters (GRF, plantar pressure parameters, and joints moments and power) were significantly different between all patient groups and controls [6]. Table 1 presents results of comparison between patient populations and controls for a few representative kinematic and kinetic parameters (The data from 14 ankle osteoarthritis and 10 total ankle replacement patients were analyzed for kinetic parameters). Besides, inter-stride variability of gait parameters showed significant differences between patients and controls. Almost all parameters measured by the ambulatory system that showed significant difference between patients and controls were also significantly ($p<0.05$) correlated with clinical scores, which indicated their convergent validity for this clinical evaluation [6,8].

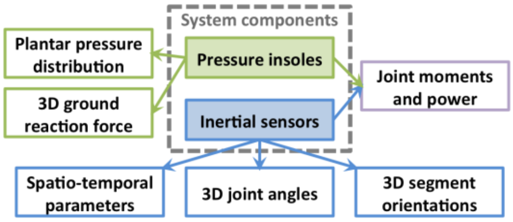

Figure 2. Contribution of each system component in measurement of different groups of gait parameters

The system is easy to use by clinicians who could install it (20~30 min), run the measurement protocol, and record the data with no need for engineers' assistance. Up to now, over 100, mainly elderly, subjects participated in our different clinical protocols and reported their gait natural and without hindrance. Use of this system is not limited to foot and ankle joints and its sensor configuration can be modified to assess other lower limb joints (e.g., knee) in different clinical protocols. In our other clinical protocols, we integrated EMG electrodes to this system and assessed several 100-meters of walking. The total weight of the introduced system was less than 1600 gr, and thus it minimally influenced natural gait. Nevertheless, the system can be further miniaturized in order to be integrated in shoes as a "wearable system for gait analysis".

CONCLUSIONS

We introduced an ambulatory system for kinematics and kinetics assessment of ankle and foot joints in long-term gait. The measured kinematic and kinetic parameters showed high levels of accuracy compared to standard gait lab instrumentation. Based on our clinical results, this accuracy was sufficient to distinguish pathological and normal gaits, and thus can be suitable for clinical evaluation. We have shown particularly that, foot and ankle kinetics impaired by ankle osteoarthritis is not completely restored after both surgeries. We suggest this system as a device for comprehensive (i.e., kinematic and kinetic) gait analysis in clinical routines.

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*Table 1. Comparison of some of measured parameters between patients and controls. Results are presented as median±IQR. * indicates significant difference (p<0.05) with controls. Ant-Post ground reaction force (GRF) is expressed in body weight%, joints moment in weight×height%, joints power in weight×height%×rad/sec, and joints range of motion (ROM) in degree.*

	Max GRF (Ant-Post)	Max Ankle Power	Max Ankle Moment (Sagittal)	Max Midtalar Moment (Sagittal)	Max Ankle ROM (Sagittal)	Midtalar ROM (Sagittal)	Ankle ROM (Transverse)
Ankle Osteoarthritis	8.4±3.5*	5.2±9.0*	6.3±0.9*	4.1±1.1*	11.1±3.2*	10.2±2.7*	6.9±4.5*
Total Ankle Replac.	7.9±4.2*	4.6±5.6*	7.0±0.7	4.4±1.1*	13.8±6.8	10.7±5.6	6.2±3.9
Ankle Arthrodesis	8.5±2.7*	3.4±5.8*	6.6±1.5	4.6±1.1*	7.7±4.0*	10.0±3.5*	5.2±1.3*
Control	14.3±6.2	21.2±14.2	7.4±0.9	5.1±0.4	14.6±0.6	13.8±6.6	8.9±8.9