ISSN 1392–1207. MECHANIKA. 2015 Volume 21(5): 414–418

Measurement of lower limb joint angle during gait in the sagittal plane with wearable system and its impact on foot loading during walking

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crossref http://dx.doi.org/10.5755/j01.mech.21.5.10869

1. Introduction

Walking involves a combination of complex movements of body segments. This is a complex interaction of control signals, force generation, structural alignment, and joint motions. The study of human walking has aroused great interests in all periods of time from mechanistic and heuristic point of view [1, 2]. Observation has been a useful part in clinical gait analysis in the past. However, observations involving the human eyes alone are not dependable [1]. That's why motion capture systems have become an integral part of the clinical decision-making process.

Through gait analysis, the kinematic and kinetic parameters of human gait events can be determined, and musculoskeletal functions can be evaluated [3-9]. Several studies [2, 4-6] present many techniques for gait analysis. A standard gait analysis method based on the motion capture system and force platform with the capability of measuring ground-reaction forces was successfully developed and applied in laboratories [2, 4]. However the standard gait analysis requires specialized locomotion laboratories, expensive equipment, and lengthy set up and post-processing times. Consequently, there is a need a wearable system to measure a lower limb joint angle during gait in the sagittal plane in daily conditions.

Some wearable systems were presented in the literature. Shih-Lun C. et al [10] proposed a wireless multi-motion capture system using five LC resonant magnetic markers. The positional accuracy for five markers was less than 2 mm. A sensor system for measuring human motion was also presented by Van Acht et al. [11]. The system consists of a number of miniature wireless inertial sensors that are attached to limbs of a person, and a PC with a wireless receiver that interprets and presents the measurement data. Each of the sensors measures 3D-acceleration, 3D-magnetization and 3D-angular speed. The angular accuracy of the calibrated system was found to be better than 3 degrees. Several studies [12, 13] explored plantar pressure during gait for various foot problems in children and adults, but to date little known about the impact of wearable measure systems on pressure distribution during walking. While examining plantar pressure distribution is of key importance to assess changes foot loading due to measurement system. The purpose of this study was first, to propose a wearable system for measurement of lower limb joint angle during gait in the sagittal plane. Second, we investigated the impact of the construction's stiffness on human gait.

2. Testing procedures

2.1. A wearable system for measurement of lower limb joint angle during gait in the sagittal plane

The proposed system enables to measure the angle between joints of lower limb in the sagittal plane. It consists of such elements as: mechanical construction, absolute measurement angular transducer (Megamotive MAB 28A, Germany), portable PC computer, and power system (24V). The construction of the measurement system is presented in Fig. 1.

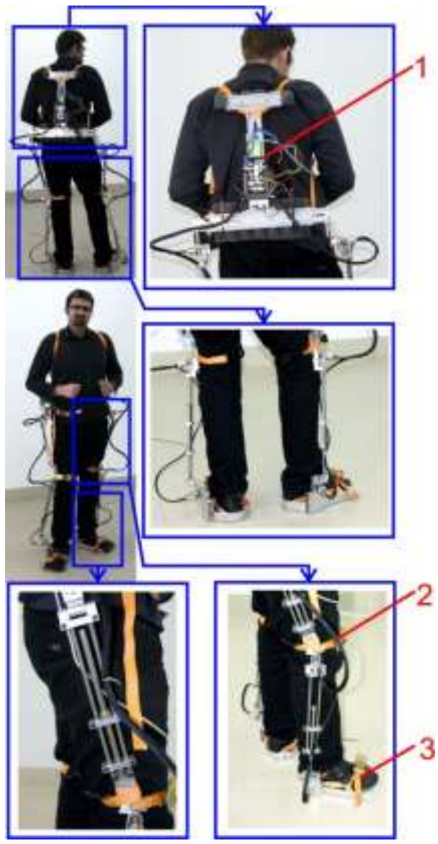


Fig. 1 Wearable system for measurement of lower limb joint angle during gait: *1* - the element placed on human back with the power system; *2* - the element placed on lower limb; *3* - the element placed on foot

The measurement system construction consists of three elements: one element placed on human back and two elements placed directly on lower limbs. It is placed on human body in five characteristic points such as: feet, back and segments between the hip joint and the knee joint (Fig. 1).

Lower limb extremity coordination is presented in Fig. 2.

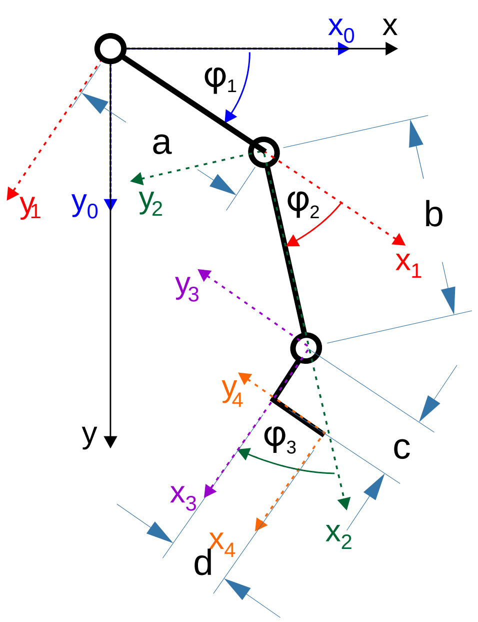


Fig. 2 Lower limb extremity coordination

The system has 23 degrees of freedom and weighs 12 kg [14, 15]. The kinematic measurement system with degrees of freedom was presented in Fig. 3.

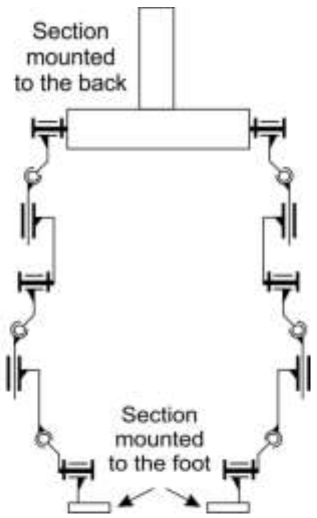


Fig. 3 The kinematic measurement system with degrees of freedom

Rotational and translational motion was realized using self-lubricating plain sleeves, which decreased the mass of the construction without stiffness decreasing. Measurement of angular displacement was realized by using six 12-bit (0-10V) resolution hall effect absolute encoder Mab28A (MegaMotive, Germany). The principle of operation was based on Hall effect sensors detecting the angular displacement axially polarized magnet by an integrated circuit having a magnetic field sensor. Transducers signal as an analog voltage from encoders was processed using DT9800 Series measuring card manufactured by Data Translation. The signal was recorded and processed using Matlab/Simulink software (Matrix Laboratory, USA). The system was calibrated using an algorithm presented in Fig. 4 prior measurement.

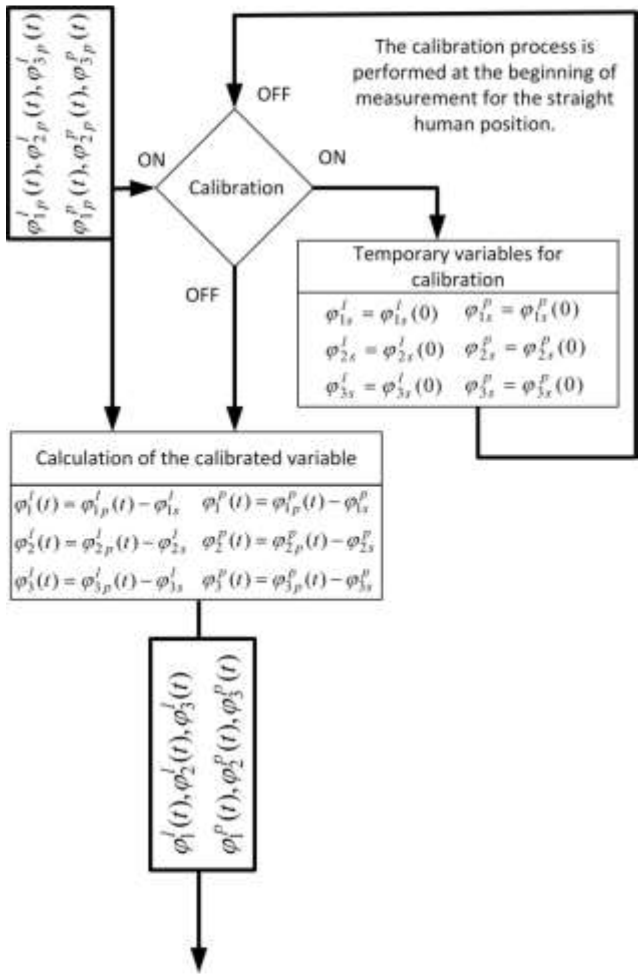


Fig. 4 The algorithm for the system calibration: φ_{1l}, φ_{2l}, φ_{3l} - the displacement in the hip/knee/ankle joint in sagittal plane after calibration; φ_{1p}, φ_{2p}, φ_{3p} - the displacement in the hip/knee/ankle joint in sagittal plane before calibration collected directly from sensors

The sampling frequency of measurement was 1 kHz.

2.2. Measurement protocol

The impact of the construction's stiffness on human gait was evaluated using pedobarograph. Ten typical subjects were randomly selected from Bialystok University of Technology (Poland). Inclusion criteria stated that subjects must be aged between 20–40 years. Exclusion criteria were any other disorders that may impact on subject's gait. All subjects received full information about the study before giving signed consent. Subject's body weight was measured using a scale with resolution of 100 g. The subject's height was measured by stadiometer. The eligible subjects were identified within two-phase measurement. In the first phase, 10 subjects were measured with a pedobarograph. In the next phase subjects were additionally equipped in wearable measurement system and measured with a pedobraograph. For measuring plantar pressure distribution, subjects walked a distance of approximately

60 meters at their habitual speed in daily conditions. Plantar pressure distribution during walking was measured with a pedobarograph (T&T medilogic Medizintechnik, GmbH Munich, Germany) based on shoe insoles with capacitive sensors (max. 240 SSR sensors per insole, depending on size and shape). The sample frequency was 60 Hz. To quantify plantar pressure distribution, the maximum magnitude of plantar pressure (peak pressure) under five anatomical masks was measured using a commercially available toolbox (Fig. 5).

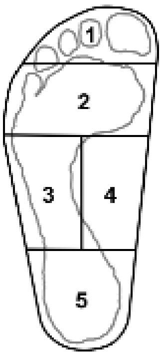


Fig. 5 Definition of different masks used in this study: Mask 1 = toes; Mask 2 = metatarsal heads; Mask 3 = lateral arch; Mask 4 = medial arch; and Mask 5 = heel

These masks are representing to the following anatomical plantar regions: the toes; the metatarsal heads; the lateral arch; the medial arch; and the heel. Maximum pressure under each anatomical region was measured per each individual step. Mean pressure was calculated by averaging the magnitude of pressure for all activated sensors in a mask for a single step. Results were expressed as means ± standard deviation (SD). A two-sample *t* test was used to determine differences in parameters for two-phase measurement. Paired *t* tests were then used to examine any differences between left and right parameters. The significance level was set at $p < 0.05$. Statistical analyses were performed using Statistica 10.0 (StatSoft, Tulsa, OK, USA).

3. Results

3.1. Measurement of lower limb joint angle during gait in the sagittal plane with wearable system

In Table 1 the comparison of the maximal displacement of ranges in lower limbs joints obtained from the measurement system and from the literature [15] was presented.

Table 1

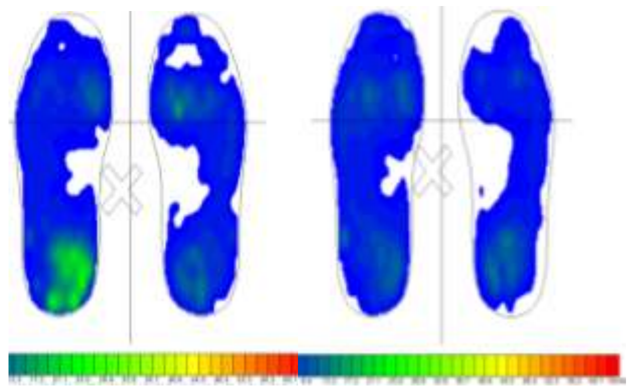
Maximal displacement of ranges in lower limbs joints

Joint	Measurement system, deg	Data from literature, deg
Hip joint flexion/extension	89/20	120/15
Knee joint flexion/extension	93/8	120/10
Ankle flexion/extension	51/35	70/20

The obtained results show that the proposed measurement system doesn’t restrict the maximal displacement of ranges in lower limbs joints. During measurement we found that the error of the measurement system was 0.225 degrees. In the system proposed in [11] the angular accuracy of the calibrated system was better than 3 degrees. Our measurement system can be used to measure of lower limb joint angle during gait in daily conditions.

3.2. The impact of the construction’s stiffness on human gait

Body Mass Index (BMI) for subjects was 25.4 (2.4). Fig. 6 illustrates plantar pressure distribution for a typical man without and with the system measurement system during walking with habitual speed.



a b

Fig. 6 Pressure distribution for: a) a typical man with measuring system; and b) a typical man without measuring system (range of pressure distribution from 1.6 to 32 N/cm^2) during walking

The initial contact for all participants was heel strike with a visually normal heel-to-toe motion. For subjects wearing measuring system, the highest magnitude of pressure distribution was found under the heel, while the lowest under the metatarsal heads. Similar pattern was observed for subjects without measuring system. Table 2 summarizes parameters extracted from pedobarograph insoles during walking for those two groups.

Table 2

Plantar pressure distribution during walking, N/cm^2

Masks	Subjects without measurement system	Subjects with measurement system	Comparison subjects without vs. subjects with measurement system p-value	95% CI
Toes Mean (SD)	4.7 (0.1)	5.7 (0.4)	p<0.05	[-1.36, -0.58]
Metatarsal Heads Mean (SD)	2.3 (0.2)	2.7 (0.5)	p<0.05	[-0.89, 0.01]
Lateral arch Mean (SD)	5.2 (0.3)	6.0 (0.6)	p<0.05	[-1.39, -0.17]
Medial arch Mean (SD)	3.9 (0.2)	5.8 (0.5)	p<0.05	[-2.37, -1.36]
Heel Mean (SD)	6.0 (1.3)	9.1 (1.2)	p<0.05	[-4.59, -1.64]

The magnitude of plantar pressure under the heel (mask 5) was significantly increased in average by 51.2% in the group wearing measuring system (6.0 ± 1.3 N/cm^2 in the group without measuring system vs. 9.1 ± 1.2 N/cm^2 in the group wearing measuring system, $p < 0.05$). Between groups significant difference was also observed for magnitude of plantar pressure under the toes (mask 1), the metatarsal heads (mask 2), the lateral arch (mask 3), and the medial arch (mask 4). Specifically, under the metatarsal heads, magnitude of plantar pressure was higher in average of 17.4% in the group wearing measuring system compared with the group without the measuring system (2.3 ± 0.2 N/cm^2 in group without measuring system vs. 2.7 ± 0.5 N/cm^2 in the group wearing measuring system, $p < 0.05$). On the same note, results show a significant increase in magnitude of plantar pressure under the toes in average of 21.3% in the group wearing measuring system (4.7 ± 0.1 N/cm^2 in the group without measuring system vs. 5.7 ± 0.4 N/cm^2 in the group wearing measuring system, $p<0.05$). Additional, the higher magnitude of plantar pressure under the medial and the lateral arch is visible in subject wearing measuring system by 48.7% (3.9 ± 0.2 N/cm^2 in the group without measuring system vs. 5.8 ± 0.5 N/cm^2 in the group wearing measuring system, $p < 0.05$) and by 15.4% (5.2 ± 0.3 N/cm^2 in the group without measuring system vs. 6.0 ± 0.6 N/cm^2 in the group wearing measuring system, $p < 0.05$), respectively.

The plantar pressure distribution (F_1-F_5) under five anatomical masks (Fig. 5) during gait with wearing and without the construction was presented in Fig. 7.

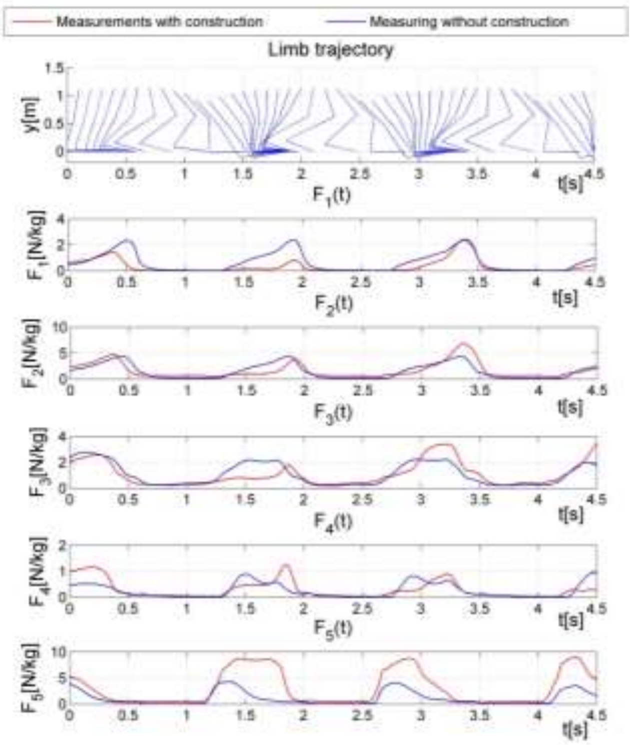


Fig. 7 The plantar pressure distribution under five anatomical masks during gait

The results show the reduction in magnitude of plantar pressure distribution under the toes during when subject wearing the measurement system. However under the heel the magnitude of plantar pressure distribution is higher when subject wearing the measurement system. Under the metatarsal heads, the lateral arch, and the medial arch, no significant differences between subjects with and without construction were observed.

4. Conclusions

The proposed system allows for measurement of lower limb joint angle during gait in the sagittal plane. The advantage of the proposed system is possibility of it's using outside regular laboratory. It is easy to use and relatively cheap. Our results show that the proposed measurement system doesn't restrict the maximal displacement of ranges in lower limbs joints. We analysed the impact of the construction's stiffness on human gait based on magnitude of pressure distribution under foot obtained from the pedobarograph. The initial contact for all subjects was heel strike with a visually normal heel-to-toe motion. For subjects wearing measuring system, the highest magnitude of pressure distribution was found under the heel, while the lowest under the metatarsal heads. Similar pattern was observed for subjects without measuring system. The results show the reduction in magnitude of plantar pressure distribution under the toes during when subject wearing the measurement system. However under the heel the magnitude of plantar pressure distribution is higher when subject wearing the measurement system. Under the metatarsal heads, the lateral arch, and the medial arch, no significant differences between subjects with and without construction were observed. The obtained results can be useful in construction another measurement systems similar to this one proposed in the manuscript.

Acknowledgements

The paper is supported by Bialystok University of Technology, project Nr S/WM/1/2012.

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MEASUREMENT OF LOWER LIMB JOINT ANGLE DURING GAIT IN THE SAGGITAL PLANE WITH WEARABLE SYSTEM AND ITS IMPACT ON FOOT LOADING DYRING WALKING

S u m m a r y

The purpose of this study was first, to propose a wearable system for measurement of lower limb joint angle during gait in the sagittal plane. Second, we investigated the impact of the construction's stiffness on human gait. The system consists of such elements as: mechanical construction, absolute measurement angular transducer, portable PC computer, and power system. The impact of the construction's stiffness on human gait was evaluated using pedobarograph. Ten typical subjects randomly selected from Bialystok University of Technology. The advantage of the proposed system is possibility of it's using outside regular laboratory. Our results results show that the proposed measurement system doesn't restrict the maximal displacement of ranges in lower limbs joints. The results show the reduction in magnitude of plantar pressure distribution under the toes during when subject wearing the measurement system. However under the heel the magnitude of plantar pressure distribution is higher when subject wearing the measurement system.

Keywords: gait analysis, pressure distribution, angle, wearable measurement system.

Received March 23, 2015
Accepted April 21, 2015