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RESEARCH ARTICLE

Verification of determining the spatial position of the lower extremity by ultrasound-based motion analyser

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Abstract

The objective of this study is to verify the ultrasound-based motion analysis method on 16 healthy people during gait. Ultrasound-based triplets were fixed onto the sacrum, the left and right thighs and the left and right calves. A ZEBRIS ultrasound-based motion analysis system was used for measuring the spatial coordinates of triplets during gait. The position of the nineteen anatomical points involved in the study was defined by an ultrasound-based pointer in the local coordinate system specified by the triplets before starting measurements. The spatial coordinates of the designated anatomical points can be calculated from the coordinate of triplets. The method is calibrated with interobserver and intraobserver variations. On the basis of the statistical analysis of the spatial coordinates specified by the ultrasound-based measurement method, it can be established that the measurement method is reproducible because in case of an experienced person performing measurements the maximum standard deviation of coordinates is below 1 mm, and around 2 mm in case of a person inexperienced in measurements.

Keywords

ultrasound-based motion analyser system · 3D kinematics · gait · inter- and intraobserver variation

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1 Introduction

Gait analysis can be described as a field of biomechanical engineering dealing with the subject of human locomotion. By means of different available measuring techniques (for example video recording) the data of human gait are captured (i.e. the gait pattern is recorded as a function of time) and further analysis and calculation are done in order to obtain all the data required for evaluating the quality of the subject's gait, including basic gait parameters (stride length, cadence, velocity, etc.), forces and moments occurring in the joints, muscle activity during each gait cycle, velocity and acceleration of each segment of the limb, etc.

Since measuring and recording techniques were developed, gait analysis has been frequently used in almost all fields of human locomotion [3]. Gait analysis can be successfully used in sport applications, post-injury assessment, disability evaluations, research analysis of injuries, industrial applications of sports product design and improvement, etc.

The successful use of gait or motion analysis in the diagnosis of patients with locomotor pathology and in the subsequent planning and assessment of treatment has been limited because of its unreliability, particularly in evaluating frontal and transverse plane components. This is critical because in patients with pathological gait, such as children with cerebral palsy, abnormalities occur essentially in these planes [4]. In skin marker-based gait analysis systems, skin movement artifacts have been shown to affect the accuracy of calculated joint kinematics much more in the frontal and transverse planes than in the sagittal plane [2]. Therefore, reduction of the effects of skin movement artifacts in the two planes will improve the quality of gait analysis data for clinical purposes.

The use of video or stereophotogrammetry in human movement analysis requires determination of the position of active or passive markers on anatomical points before calculation of the kinematics and kinetics of body segments.

The ultrasound-based measuring method developed by Kocsis [7] is based on the following fundamental axioms:

1 The musculoskeletal system is generally modelled as a multi-link chain with each body segment (pelvis, thigh, shrank,

foot) as a rigid link [9].

2 An array of three points per rigid body is needed and is sufficient for the definition of a body-embedded local reference frame, which represents the position and the orientation of the rigid body. The three points are named the fundamental points of the local reference frame. The position of an anatomical point on the segment could be determined by its position in relation to the fundamental points. Before the dynamic measurement is undertaken, the position of investigated anatomical points in relation to the fundamental points has to be recorded.

In the method the three fundamental points of the rigid body are the three markers per segment, determining the segment-embedded reference frame. The position vectors of anatomical points in the segment-embedded reference frame are determined before the measurement during the so-called calibration phase [7]. The use of this approach provides an opportunity to attach markers anywhere on a visible part of the segment and to analyse not just the visible lateral anatomical points but also the medial, anterior, and posterior anatomical points. The various spatial-temporal parameters and joint kinematics could be determined from the spatial coordinates of investigated anatomical points [5].

The ultrasound-based method is not verified / validated by statistical methods. Thereafter, a validation of the method will be presented on the basis of repeated intraobserver and interobserver measurements on healthy subjects.

2 Material

The spatial position of anatomical points of lower extremities was determined on 16 healthy subjects using the method to be described below. Only people without any clinical history of diseases or injuries in the lower extremities were involved in the study. There were 8 males (mean age 28.17±7.69 years, mean height 178.42±7.20 cm, mean weight 77.89±11.80 kg) and 8 females (mean age 25.09±4.21 years, mean height 168.07±5.70 cm, mean weight 59.86±6.38 kg) The tests were authorized by the Science and Research Ethics Committee of Semmelweis University. Each voluntary subject provided an informed written consent to performing the tests in advance.

3 Method

3.1 Measurement Instrument

A ZEBRIS CMS-HS (ZEBRIS, Medizintechnik GmbH, Germany) computer-controlled ultrasound-based motion analysis system – located at the Biomechanical Laboratory of the Department of Applied Mechanics of the Budapest University of Technology and Economics – was used for the biomechanical modelling of the gait. The system consists of the following components:

- central unit connected to a PC-based computer;
- MA-HS measurement head with three transmitter sensors emitting ultrasound signals;
- TS-LU triplet containing three active markers, to be fixed on to the sacrum, left and right thighs and left and right calves;
- pointer with two ultrasonic markers to specify anatomical points.

Identification of the fundamental points and the investigated anatomical points based on Kocsis [7]

The measurement head with three transmitters, emitting ultrasound signals at specific intervals, which are recorded by the active markers (the measurement frequency being 100Hz) is located on the back of the person (Fig. 1). In the knowledge of the speed of ultrasound, the distance between each marker and the measurement head transmitters can be calculated from the time delay of the transmission. In the knowledge of the distance between the active markers and each of the three transmitters of the measurement head and the spatial coordinates of the transmitters, the spatial coordinates of the markers can be calculated using the method of triangulation at each moment of time during the measurement [7].

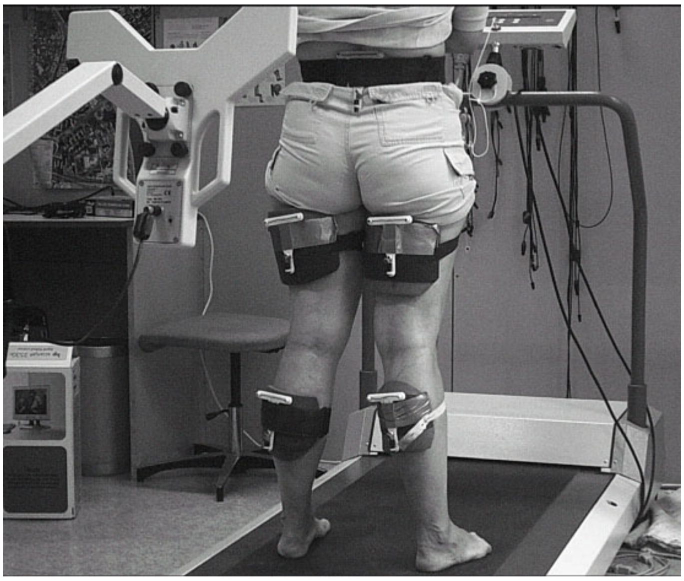

Fig. 1. Arrangement of measurements

A fundamental assumption of biomechanical models is that the segments of the lower extremities can be modelled as rigid bodies and all motions are generated in the joints [9]. The position and the orientation of a segment of the human body are determined by the position of three points per segment, named fundamental points. The position of an anatomical point of the same segment could be determined by its position in relation to the fundamental points. This means that before the measurement the position of the investigated anatomical points should be determined in relation to the fundamental points. The position of the anatomical points of a segment in relation to the fundamental points (in this case the three markers) was specified by an ultrasound-based pointer during the calibration phase

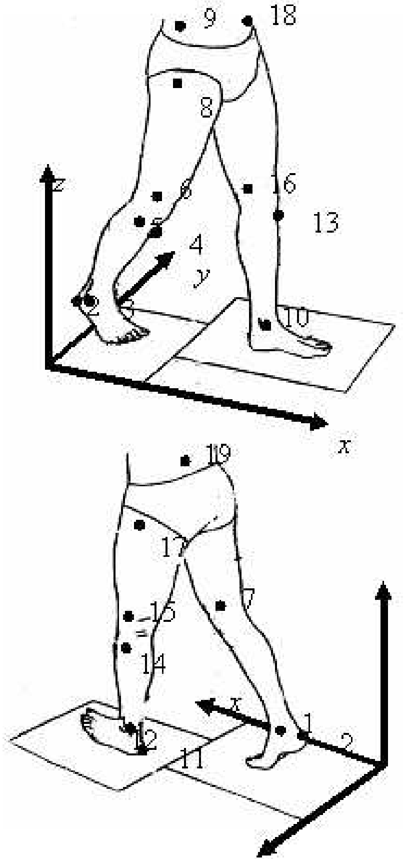

Fig. 2. Position of the anatomical points. (1) right medial malleolus, (2) right heel, (3) right lateral malleolus, (4) right tibial tubercule, (5) right head of fibula, (6) right lateral femoral epicondyle, (7) right medial femoral epicondyle (8) right greater trochanter, (9) right ASIS, (10) left medial malleolus, (11) left heel, (12) left lateral malleolus, (13) left tibial tubercule, (14) left head of fibula, (15) left lateral femoral epicondyle, (16) left medial femoral epicondyle (17) left greater trochanter, (18) left ASIS, (19) sacrum.

before measurement [7]. During motion the position of the fundamental points of each segment of the human body has to be measured by the ultrasound device. A computer code calculates – on-line – the position of the investigated points from the position of the fundamental points using the position vector of investigated anatomical points in a local coordinate system defined by markers. The spatial coordinates of any number of anatomical points can be specified using the method described above. During measurement, the ArmModel software connected to the system promptly calculates, continuously records, numerically stores, and displays the spatial position of anatomical points [7].

The anatomical points are fixed to the local coordinate system by a pointer during the calibration phase. The relative position vectors are constant, what means that even the skin is moving on the hypothetical anatomical point; the calculation does not take this into consideration. The triplets and the fixation together reduce skin motion. It is important to check whether the triplet is stable. During the measurement the software calculates the distances between the greater trochanter and the lateral femoral epicondyle, the lateral malleolus and the tibial tubercle, the medial and the lateral femoral epicondyle. If those distances are constant during the motion, the triplets are stable; if those distances are not constant, the triplets are repositioned during the measurement, and the whole procedure has to be repeated.

3.2 Biomechanical Model

The model developed by Knoll et al.[6] consists of 19 anatomical points identified by the position of fundamental points on segments and by the distances between the fundamental points and the anatomical points. The medial and lateral malleolus, the heel, the head of fibula and the tibial tubercle are linked to three fundamental points on the calf, the medial and lateral femoral epicondyle and greater trochanter to three fundamental points on the thigh, the left and right anterior superior iliac spine to three fundamental points on the sacrum (Fig. 2). The model is simple, and is adjustable for each person studied.

3.3 Process of Measurement Method

The subjects wore shorts and no shoes to allow access to anatomical points of the lateral and medial malleolus and the heel. The subjects walked on a motorized treadmill (Bont Zwolle B.V. Austria); the walking area of the treadmill belt was 330 mm· 1430 mm. The treadmill was set at a constant speed of 3.0 km/h. The advantages of using a treadmill for gait analysis are that it allows a convenient application of monitoring equipment and provides a controlled setting by which multiple gait cycles can be analysed. In our measurements, each subject performed one successful trial including at least six gait cycles. Walking on the treadmill can initially be an unfamiliar experience. This in turn can influence the parameters measured. Therefore, the measurement starts after six minutes of familiarization time as suggested by Alton et al [1] and Matsas et al [8]. The main steps of the 40 to 50 minute examination are as follows:

- A triplet fastened on to each of the sacrum, the left and right thighs and the left and right calves (Fig. 1) are all connected to the measurement system using cables and the data capture unit according to channel distribution.
- In the course of calibration, the person performing the test uses the ultrasound-based pointer to identify anatomical points and record the position vector of the anatomical points in the local coordinate system defined by the triplets.
- In the course of six movement cycles, the spatial coordinates of the designated anatomical points are detected and recorded by the measurement control software.

3.4 Design of Experiments

The first step of introducing any new method is to validate the measurement method by a statistical method. It means to determine the interobserver and intraobserver variation of measurements by two different observers.

Observer 1, who is experienced in examining, places the ultrasound-based triplets, as described above, onto the segments

Tab. 1. Statistical parameters characterizing the interobserver and intraobserver variations of the measurement method

		Intraobserver						Interobserver	
		Observer 1			Observer 2				
Angle of knee angle	Coordi-nate	Standard deviation of coordinates	95% confi dence	F test	Standard deviation of coordinates	95% confi-dence	F test	Average difference	95% confi-dence
10 deg.	X	0.456	0.487	159.698	0.777	0.749	145.049	3.564	3.085
	Y	0.512	0.514	87.520	0.812	0.887	110.972	3.323	3.267
	Z	0.543	0.543	125.177	0.715	0.706	72.707	3.453	3.741
20 deg.	X	0.456	0.414	121.342	0.859	0.832	73.586	3.121	3.041
	Y	0.432	0.461	129.193	0.878	0.809	104.994	3.347	3.627
	Z	0.456	0.414	93.963	0.888	0.843	163.277	3.275	3.859
40 deg.	X	0.515	0.600	83.003	0.612	0.579	163.629	3.236	3.876
	Y	0.567	0.549	101.259	0.655	0.633	117.104	3.867	3.835
	Z	0.543	0.562	131.797	0.608	0.591	104.424	3.921	3.140
60 deg.	X	0.512	0.551	88.373	1.123	1.128	100.014	3.169	3.316
	Y	0.456	0.554	129.739	1.347	1.096	158.040	3.284	3.227
	Z	0.343	0.592	113.553	1.234	1.089	135.877	3.451	3.798

and connects them to the system and identifies the anatomical points to be examined using the ultrasound-based pointer in the course of calibration. Subjects walk on the treadmill for a minimum of 5 minutes. During the motion the spatial coordinates of the anatomical points are determined by the method. The measurement above is also performed by Observer 2, who is inexperienced in designating the points.

3.5 Statistical Analysis

The intraobserver variation of the measurement represents the standard deviation of spatial coordinates determined by measurements performed on the same subject with the same person performing the examination. The interobserver variation of the measurement represents the average difference between spatial coordinates determined by measurements on the same subject with two different people performing examinations. The statistical analysis required to identify the inter- and intraobserver variations were performed by the computer software named Statistica (version 7, 2004.).

In order to identify the inter- and intraobserver variations, the following formula was used to calculate the knee angle [5], which is the spatial angle between the spatial vectors joining the lateral malleolus to the head of the fibula and joining the lateral femoral epicondyle to the greater trochanter. The coordinates of the anatomical points were selected at knee angles of 10, 20, 40, and 60 degrees, respectively. In order to specify the intraobserver variation, the standard variation of coordinates was calculated for both investigators and an F-test was performed. The F-test was considered to be statistically significantly different if $p < 0.05$. The width of the 95% confidence intervals was determined from the standard deviation of five subsequent measurements.

In order to specify the interobserver variation, the coordinates of the anatomical points were selected at knee angles of 10, 20, 40, and 60 degrees. The average of the differences in the spatial coordinates specified in the course of the measurements performed by the two persons as well as the width of the 95% confidence intervals was calculated.

4 Results

For the sake of transparency, the results of verification and error calculations are summarized in Table 1. Statistical features are determined separately for each of the three spatial dimensions.

Table 1 shows the characteristic statistical parameters of the intraobserver variation for two people performing measurements as well as the statistical features of the interobserver variation between the two observers. In case of an experienced person (Observer 1) performing measurements, the maximum standard deviation of coordinates to directions x, y, and z are 0.515, 0.567, and 0.543 mm; in case of an absolutely inexperienced person (Observer 2) performing measurements, the same values are 1.123, 1.347, and 1.234 mm, respectively.

In the event of interobserver variation, the average differences of coordinates in directions x, y, and z are 3.564, 3.867 and 3.921 mm, which still also fall within the range of values to be found in the literature [4].

5 Conclusion

The method – the ZEBRIS ultrasound-based measurement system with ArmModel measurement control software – was verified by intra- and interobserver variation calculations.

On the basis of the statistical analysis of the spatial coordinates (Table 1) specified by the measurement method developed by Kocsis [7], it can be established that the measurement method is reproducible because in case of an experienced person performing measurements the maximum standard deviation of coordinates is below 1 mm, and around 1 mm in case of a person inexperienced in performing measurements. In case of an experienced person performing measurements, the standard deviation of coordinates is much lower than in case of a less experienced person and it is nearly the same as the values specified in the course of measurements by experienced persons in the case of the video-based system [4]. The most probable reason for such difference is that the measurement accuracy of an ultrasound-based motion system is higher than that of a video-based one. A higher interobserver variation can be explained by the fact that the tests were performed on humans and the diameter of the determinable surface of the anatomical points included in the investigation approximately corresponds to this value. However, it is reflected in measurement analysis that errors can be reduced by practice as in the case of experienced persons performing measurements the differences between coordinates are below 1 mm.

Analysis of the results in Table 1 also shows that the standard deviation of the coordinates is nearly identical at various knee angles and the direction of coordinates does not substantially affect the value of standard deviation, either. The results of the F-test show that there is no significant difference between the coordinates, with distribution being normal.

A usable method for gait analysis was demonstrated which, it is believed, is suitable for use in clinical settings. Inter- and intraobserver studies suggest that the method is reliable. The measurements are fast and easy to perform. On the basis of the results yielded, it can be established that the measurement system can be used for describing the gait patterns for both healthy and injured subjects.

References

1 **Alton F, Baldey L, Caplan S, Morrissey MC**, *A Kinematic Comparison of over Ground and Treadmill Walking*, Vol. 13, 1988.

2 **Andrews JG, Euler's and Lagrange's equations for linked rigid-body models of three-dimensional human motion**, Three-Dimensional Analysis of Human Movement: Human Kinetics (Allard P, Stokes IAF, Blanchi JP, eds.), Chanoaign, 1995, pp. 145–175.

3 **Gage J.R.**, *Gait analysis in cerebral palsy*, MacKeith Press, London, England, 1991.

4 **Cappozzo A, Catani F, Leardini A, Benedetti MG, Della Croce U**, *Position and orientation in space of bones during movement: experimental artifacts*, Clinical Biomechanics **11** (1996), 90–100.

5 **Jurák M, Kocsis L**, *Measurement Method and Calculation Package for Gait Analysis Using Instrumented Treadmill*, Proceedings of the Third Conference on Mechanical Engineering, Budapest, 2002, pp. 372–380.

6 **Knoll Zs, Kocsis L, Kiss RM**, *Gait Patterns before and after Anterior Cruciate Ligament Reconstruction*, Knee Surgery Sports Traumatology Arthroscopy **12** (2004), 7–13.

7 **Kocsis L**, *More precise measurement method for gait analysis*, Proceedings of the third conference on mechanical engineering, Budapest, 2002, pp. 843–847.

8 **Matsas A, Taylor N, Mcburney H**, *Knee joint kinematics from familiarized treadmill walking can be generalized to over ground walking in young unimpaired subjects*, Gait and Posture **11** (2000), 46–53.

9 **Winter DA**, *Biomechanics and Motor Control of Human Movement*, Wiley, New York, 1979.