Influence of Body Features in Soccer Athlete's Gait Variability

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Abstract

The purpose of the present study was to investigate the correlation between certain body features of healthy male soccer players and gait variability. The acceleration signal of the three axes of motion produced during gait was measured and processed with the Gait Evaluation Differential Entropy Method (GEDEM). GEDEM calculates an index for every axis of motion and provides a quantitative tool of gait evaluation. Seventy five healthy male soccer athletes were examined with the triaxial accelerometer system in order to objectively evaluate the characteristics of the motion in a 30 second walking test and the data obtained were analyzed with GEDEM.

Among the examined body features the absolute difference in right-left thigh circumference was significantly correlated with the GEDEM value constituting a prognostic factor.

Triaxial accelerometry with GEDEM provides adequate evaluation for gait variability and could be a helpful tool for the estimation of soccer athlete's musculoskeletal condition.

Key Words: gait analysis, biosignal variability, body features

1. Introduction

Various approaches have already been used for the study of functional ability of an individual [10]. These techniques can neither be applied in an everyday practice nor in a population such as soccer athletes, as they are time-consuming, specialized, and expensive and they demand a complicated laboratory set-up.

Different procedures, including classification of movements, assessment of physical activity level, can be reliably evaluated using a single triaxial accelerometer worn at the waist [10]. Various types of accelerometers have been developed in order to estimate human movement and some of them are useful in clinical practice. Body acceleration can be recorded repetitively and objectively, without effecting body's behavior or exposing it to any radiation [5] - [6].

Shannon [15] formulated the information theory of entropy. According to that, the entropy of a system is associated with the uncertainty of the result. Therefore, biosignals with high probability for periodical behaviour are characterized by low differential entropy. Contrarily, biosignals following a random distribution have higher values of statistical entropy [16]. Entropy can be used as an index to estimate the uncertainty in human walking signal. Low entropy values are equivalent to more repeatable movements, while subjects unable to perform harmonic motion demonstrate high entropy values.

In previous studies, the *Gait Evaluation Differential Entropy Method* (GEDEM) has been used to differentiate *Lumbar Spinal Stenosis (LSS)* patients from healthy subjects [12] - [13] and to follow-up these patients postoperatively. GEDEM has also been used for differentiating ACL injured people from healthy subjects and for monitoring these people postoperatively [17] – [18].

In the present study the gait evaluation differential entropy method *(GEDEM)* was applied in a population of healthy male soccer players. The values of several body features were recorded and the correlation between the *GEDEM* index and these parameters was calculated.

2. Materials and Methods

2.1. Subject selection criteria

Between December 2012 and May 2014, seventy five (75) healthy male soccer athletes were examined (age 18.78±5.23years, height 1.75±0.06m, weight 69.00±0.02kg, Body Mass Index (BMI) 22.46±2.19kg/m^2). Eight soccer teams participated in the study, from the region of Rethymnon (Crete) and Athens.

Their GEDEM values were calculated based in accelerometer data that were measured with the use of a triaxial accelerometer. Parameters such as height and weight were also recorded. The *axis of the 1st metatarsal (hallux valgus deformity)* as well as the presence or not of *flatfoot* of both feet, were also recorded.

Athletes were training two to five times per week and were participating in a weekly football game in their local championships. The study protocol was approved by the Ethics Committee of the University Hospital of Heraklion. All subjects signed an informed consent form in accordance with the requirements of the Institutional Review Board of the University Hospital of Heraklion. For minors, athletes younger than 18 years of age, written consent was signed by their parents or guardians.

2.2. Device description

The measurement device was described in details in a previous study [12]. Accelerations data from the *anterior-posterior (x), medio-lateral (y) and vertical (z) axes* were recorded during each walking trial and analyzed with the proper software.

2.3. Measurement Procedure

All measurements took place in the training field of every team and were performed during the afternoon training program of the teams. Subjects were instructed to wear light clothing that allowed comfortable movement and a pair of socks to prevent influence of ground factors during walking. Any necessary precaution was taken in advance, in order to keep the subjects calm and concentrated during the trial.

Every examined athlete underwent three main stages of evaluation. Past medical history including general health status and musculoskeletal disorders or injuries was taken. Demographic data as well as occupation, and frequency of training were recorded too. A detailed clinical examination of the musculoskeletal system was followed [7]. The *length of left and right lower limb*, the *circumference of left and right thigh calf* of all participants were measured. The *differences between right and left lower limb length*, *right and left thigh circumference* and *right and left calf circumference was calculated* . The *axis of the 1st metatarsal (hallux valgus deformity)* as well as the presence or not of *flatfoot* of both feet, were also recorded. Athletes underwent three subsequent gait measurements, with the accelerometer device.

The sensor was positioned close to the center of gravity *(COG)* of the human body **[Figure** *1***]**, considered central with respect to the sagittal plane [4]. The device was attached to the subject's body, with a flexible belt around the waist in a stable way, so it was free to move with respect to the skin, over the middle part of the lower back (medial lumbar region, over the L3 process). The *COG* reflects body motion and has an important role in maintaining the dynamic stability during walking [2] – [3]. The measurement device was designed to cause the minimum disturbance on subject's walking. All subjects were asked to walk for approximately 30 *m* in a straight direction, at a comfortable and self-selected free-walking speed. The walking ground was dry and flat, with no obstacles across the walking direction. Measurements were cancelled when the wind speed exceeded 2 *m/s*. The measurement duration was 30 *sec* and the sampling rate for every axis was 128 *Hz*. At the end of each measurement, the subject approached the computer and the gait acceleration data were transferred from the sensor to the computer through a USB port. Every acceleration measurement was recorded and processed. Personal data, medical history and gait acceleration data were collected into the data acquisition software and a tagged ASCII file on the hard disk was generated.

Figure 1. A young athlete prepared for the walking trial, wearing already the accelerometer device in a stable way around his waist, close to the centre of gravity.

2.4. Accelerometer Data Analysis

A *GEDEM* index was calculated for the *anterior-posterior (x), medio-lateral (y) and vertical (z) axes* for every measurement and an average *GEDEM* value was calculated at the end of the three measurements for every individual and every axis. The first and the two last (2) gait cycles were removed, because it was deemed that acceleration and deceleration could contribute to variability bias. The *e* logarithmic base was used here and so the entropy units were measured in *nats*.

2.5. Statistical Analysis

The mean *GEDEM* value of every individual was used for the statistical analysis. The *Kolmogorov–Smirnov test* was applied to evaluate distributions for normality analysis of the parameters. Comparison of categorical factors with the dependent variables was performed using: a) the one-way *ANOVA* model, b) the *independent samples t-test*, c) *stepwise multiple regression*. Correlations between continuous and dependent variables were evaluated using the Pearson correlation coefficient. All tests were two-sided and statistical significance was set at $p<0.05$. The analyses were carried out using the statistical package *SPSS*, version 15.0 (*SPSS* Inc., Chicago, IL, USA) for *Windows*®.

3. Results

The study group consisted of 75 healthy male soccer athletes. The participants had no history of neurological, musculoskeletal, respiratory, cardiovascular diseases or any recent injury.

In **Table 1** are presented the mean, median, standard deviation, minimum and maximum values for the first set of the parameters.

Table 1. Values of body features recorded in the study group of the healthy soccer athletes - values in *cm.* (∗values in *degrees*)

Characteristics (N=75)	Mean	Median	S.D.	Minimum	Maximum
Left Lower Limb Length	90.45	91.00	3.88	81.00	99.00
Right Lower Limb Length	90.42	90.50	3.94	80.00	97.50
Left Thigh Circumference	48.36	48.50	3.55	40.00	56.50
Right Thigh Circumference	48.84	48.50	3.70	40.50	57.00
Left Calf Circumference	37.02	37.00	2.22	31.50	41.50
Right Calf Circumference	37.21	37.50	2.23	31.50	42.00
Right-Left Lower Limb Length Difference	0.35	0.50	0.46	0.00	3.00
Right-Left Thigh Circumference Difference	0.92	1.00	0.79	0.00	3.50
Right-Left Calf Circumference Difference	0.41	0.50	0.46	0.00	2.00
Hallux Valgus∗ **Yes:71** **No:4**	10.67	10.00	5.71	0.00	25.00

The correlations between the various control body variables and entropy values in the three planes are given in **Table 2.** In the same table are presented the results of correlation analysis in the subgroup of athletes with *no flatfoot deformity (N=42)* and the corresponding results in the subgroup with *flatfoot deformity (N=33).*

Table 2. Correlations of control variables with values of the gait evaluation differential entropy method *(GEDEM)* index in *x, y and z* axes in: a. male soccer players b. male soccer players with no flatfoot deformity c. male soccer players with flatfoot deformity, during a 30 *sec* walking test - values in *cm.* (∗values in *degrees*)

Body variables	**Statistic Parameter**	**Characteristics (N=75) (the whole subject's groop of soccer players)**			**Characteristics (N=42) (no flatfoot deformity)**			**Characteristics (N=33) (flatfoot deformity)**		
		Entropy x (nats)	**Entropy y (nats)**	**Entropy z (nats)**	**Entropy x (nats)**	**Entropy y (nats)**	**Entropy z (nats)**	**Entropy x (nats)**	**Entropy y (nats)**	**Entropy z (nats)**
Left Lower Limb Length	Pearson's (r)	-0,125	-0,075	-0,064	-0,095	-0,062	-0,044	-0,116	-0,082	-0,026
	p-value	0,285	0,524	0,584	0,548	0,696	0,78	0,52	0,648	0,886
	N	75	75	75	42	42	42	33	33	33
Right Lower Limb Length	Pearson's (r)	-0,142	-0,09	-0,059	-0,115	-0,088	-0,029	-0,124	-0,062	-0,029
	p-value	0,225	0,444	0,613	0,466	0,579	0,853	0,493	0,734	0,871
	N	75	75	75	42	42	42	33	33	33
Left Thigh Circumference	Pearson's (r)	-0,102	-0,041	0,144	-0,136	-0,131	-0,002	-0,17	0,163	0,279
	p-value	0,385	0,728	0,217	0,389	0,407	0,989	0,343	0,364	0,116
	N	75	75	75	42	42	42	33	33	33
Right Thigh Circumference	Pearson's (r)	-0,15	-0,059	0,007	-0,158	-0,126	-0,151	-0,29	0,043	0,136
	p-value	0,2	0,616	0,952	0,317	0,425	0,34	0,101	0,812	0,449
	N	75	75	75	42	42	42	33	33	33
Left Calf Circumference	Pearson's (r)	-0,224	-0,045	0,035	-0,19	-0,092	-0,09	-0,38	0,029	0,151
	p-value	0,053	0,702	0,763	0,228	0,561	0,571	0,029	0,872	0,4
	N	75	75	75	42	42	42	33	33	33
Right Calf Circumference	Pearson's (r)	-0,241	-0,073	0,01	-0,237	-0,134	-0,137	-0,349	0,023	0,145
	p-value	0,037	0,533	0,934	0,131	0,398	0,388	0,047	0,899	0,419
	N	75	75	75	42	42	42	33	33	33
Right-Left Lower Limb Length Difference	Pearson's (r)	-0,114	-0,071	-0,001	-0,214	-0,149	-0,04	0,172	0,373	0,066
	p-value	0,33	0,546	0,991	0,174	0,347	0,8	0,338	0,032	0,714
	N	75	75	75	42	42	42	33	33	33
Right-Left Lower Limb Thigh Circumference Difference	Pearson's (r)	-0,197	-0,042	-0,3	-0,135	-0,047	-0,241	-0,377	-0,072	-0,443
	p-value	0,09	0,719	0,009	0,395	0,765	0,124	0,031	0,689	0,01
	N	75	75	75	42	42	42	33	33	33
Right-Left Lower Limb Calf Circumference Difference	Pearson's (r)	0,073	0,192	-0,032	0,108	0,218	0,057	-0,04	0,094	-0,229
	p-value	0,532	0,099	0,788	0,494	0,165	0,719	0,825	0,603	0,199
	N	75	75	75	42	42	42	33	33	33
1st Metatarsal Axis (0-5 degrees)	Pearson's (r)	0,33	0,385	0,313	0,628	0,547	0,523	0,009	0,263	0,107
	p-value	0,134	0,076	0,156	0,052	0,102	0,12	0,977	0,408	0,741
	N	22	22	22	10	10	10	12	12	12
1st Metatarsal Axis (10-15 degrees)	Pearson's (r)	-0,074	0,278	0,123	-0,027	0,37	0,154	-0,253	-0,088	0,024
	p-value	0,646	0,078	0,443	0,899	0,076	0,473	0,327	0,737	0,927
	N	41	41	41	24	24	24	17	17	17
1st Metatarsal Axis (20-25 degrees)	Pearson's (r)	-0,297	-0,439	0,236	-0,297	-0,445	0,255	-	-	-
	p-value	0,349	0,154	0,459	0,474	0,269	0,542	-	-	-
	N	12	12	12	8	8	8	4	4	4

There was noticed a low negative correlation *(r=-0.224)* almost statistically significant *(p=0.053)* between *right calf circumference* and *average differential spectral entropy values* in *x-axis* and also a low negative correlation *(r=-0.241)* statistically significant *(p=0.037)* between *left calf circumference* and *average differential spectral entropy* values also in *x-axis*.

There was a moderate negative correlation *(r=-0.300)*, statistically significant *(p=0.009)* between *right-left thigh circumference difference* and *average differential spectral entropy* values in *z-axis*.

Thirty three subjects were characterized by flat foot. In athletes without *flatfoot deformity* there was noticed only a positive strong correlation *(r=0.628)* almost statistically significant *(p=0.052)* in *x-axis*.

On the other hand the population with flatfoot deformity exhibited moderate negative correlation statistically significant between *Left Calf Circumference (r=-0.380, p=0.029)* and *x-axis* as well as between *Right Calf Circumference (r=-0.349, p=0.047)* and *x-axis*. There was also a strong negative correlation *(r=-0.443)* statistically significant *(p=0.010)* between *Right-Left Lower Limb Length Difference* and *z-axis.*

Statistical analysis was performed by means of *stepwise multiple regression* and the results are presented in **Table 3** for *x, y* and *z-axes*.

Table 3. Stepwise multiple regression analysis for *anterior-posterior (x), medio-lateral (y) and vertical (z)* axes.

Depend. Var. / Differ. Entr. Axis	**anterior-posterior (x) axis**			**medio-lateral (y) axis**			**vertical (z) axis'**			**vertical (z) axis''**		
	Regression coefficients	**Std. Error**	**p-value**	**Regression coefficients**	**Std. Error**	**p-value**	**Regression coefficients**	**Std. Error**	**p-value**	**Regression coefficients**	**Std. Error**	**p-value**
Constant	0.620	0.058	0.0005	1.479	0.068	0.000	-0.074	0.049	0.137	-0.082	0.047	0.05
Right-Left Lower Limb Length Difference	-0.096	0.091	0.293	0.095	0.106	0.372	-0.026	0.076	0.736	-	-	-
Right-Left Thigh Circumference Difference	-0.067	0.047	0.155	0.026	0.054	0.631	0.157	0.039	<0.0005	-	-	-
Right-Left Calf Circumference Difference	-0.038	0.088	0.667	0.086	0.103	0.405	0.048	0.074	0.519	-	-	-
Difference in right-left lower circumference thigh	-			-			-			0.159	0.039	<0.0005
	R^2=5% p=0.321			R^2=2.6% p=0.599			R^2=19.4% p=0.001			R^2=19% p=0.0005		

The *right-left thigh circumference difference (THIGHDIF)*, is a prognostic factor for entropy values in *z-axis* as it is concluded from stepwise multiple regression method and the equation is:

z-axis Differential Entropy = – 0.082 + 0.159 x (THIGHDIF)

4. Discussion

In the present study a new method for the gait evaluation was applied in a population of healthy male soccer players. The proposed method examined the correlation between several body features (*length of left and right lower limb, the circumference of left and right thigh and the circumference of left and right calf)*, as well as the differences in these values between the two limbs, with the acceleration values that were obtained by the accelerometer device.

There was a variation between subjects regarding the examined characteristics which might be attributed to the wide age range of the group *(min=13 years old, max=35 years old)* the BMI index *(min=16.90 kg/m^2, max=28.68 kg/m^2)* and probably the variable training activity.

During walking, the gait periodicity of a healthy individual is high. On the contrary the gait pattern of an injured subject or of these individuals with musculoskeletal problems could exhibit deviations from its normal periodicity. As a result, healthy subjects are expected to present relatively low *GEDEM* values, whereas unhealthy or injured subjects are expected to show relatively high *GEDEM* values [1], [18].

The acceleration signals in the three axes of motion *(anterior–posterior, medio-lateral and vertical)* were measured in the present study, during a free-walking speed test for every participant. From the three diagrams of acceleration signals in the time sequence, it is excluded that the mean values of acceleration in the three planes differ, as the human body moves in a walking pattern at a free-selected speed.

Since the subjects belonged to a relatively homogeneous population (healthy male soccer athletes with similar training level and not very divergent body features), the most of the body parameter statistics showed no specific correlation with the *GEDEM* values measured. The results suggest that young healthy soccer athletes exhibit *GEDEM* values that are not influenced by body variables such *length of left/right lower limb*, *circumference of left/right thigh* and *circumference of left calf*. The *GEDEM* values did not differ significantly among these three factors. Our results are in consistence with the study of *Korhonen et al* [8]. They suggested that there is not any relationship between leg asymmetry and leg dominance.

Nevertheless, the *circumference of right calf* exhibited a low negative correlation to the *GEDEM* values at *x-axis* and *left calf circumference* demonstrated also a low negative correlation almost statistically not significant with *average differential spectral entropy values* in the *x-axis*. These results could represent a minor influence of *calf circumference* on acceleration at the *x-axis*. There was a moderate correlation, statistically significant between *absolute difference of left/right thigh circumference* and *average differential spectral entropy values* in *y-axis*. This could suggest that the difference in *thigh circumference* between the two limbs influence the gait pattern concerning the mediolateral acceleration and therefore the periodicity during walking. Finally there was not any remarkable correlation between 1st metatarsal axis and any entropy value.

Statistical analysis was performed by means of stepwise multiple regression and the results are presented in **Table** 3.**3** for *x*, *y* and *z* axes.

None of the above variables is a prognostic factor of entropy in axes *x, y,* apart from *absolute difference in right-left thigh circumference (THIGHDIF)*, which is a prognostic factor for entropy values in vertical axis as it is concluded from stepwise multiple regression method and the equation is:

$$z\text{-axis Differential Entropy} = -0.082 + 0.159 \times (\mathit{THIGHDIF})$$

Accelerometry has been shown to be an adequate mean of assessing physical activity and musculoskeletal conditions [14]. It can also provide quantitative measures of gait, identifying specific gait changes in older adults and in people who fall, and can be used objectively to quantify ambulatory activity levels [10]. It is necessary to develop objective methods for gait evaluation because clinical observation of gait can be subjective, qualitative and sometimes inconsistent, particularly when the observers have had little experience [11]. The use of accelerometer in gait analysis is enforced by Lee et al [9] study. They found that a single inertial sensor can be used as a valid means of measuring COM vertical acceleration and can detect changes in the COM vertical acceleration that may change with running velocity.

The special tests performed as part of the physical examination of athletes with musculoskeletal injuries require skills, but do not ensure accuracy [7]. Thus, other objective methods including gait evaluation are needed.

The availability of acceleration sensors of low weight (1–5 *gram*) and small dimensions (5–8 *mm*) makes possible the development of specific instruments to measure and record the acceleration of the motion of the human body in real time with negligible effects on the body's behaviour. Accelerometry applied by *GEDEM* is painless, inexpensive and non-invasive, does not require the administration of radiation or other chemical substances, and is fast enough to give an objective evaluation of the periodicity of human walking in few minutes. *GEDEM* and accelerometry can provide trainers and doctors with objectives indices data that show the gait variability of an athlete.

As it was already mentioned before, several investigators have already noticed the influence of body symmetry in performance and this could also affect the predisposal of an athlete to minor or major musculoskeletal injuries. The concluded differences in this homogenous population are noticeable and with further studies could offer a useful tool for modifying an existing training program or for predicting a possible future injury.

5. Conclusion

The tri-axial accelerometer device presented in this study is easy to use for both subjects and testers and *GEDEM* provides a reliable method for gait analysis. Measurements can be made at sports field with low cost and negligible effects on subjects and through this procedure it is easy to evaluate athlete's musculoskeletal condition with respect to gait variability. Previous studies in this area were limited by the requirement of fixed laboratory equipment and the use of paced walking procedures. Further studies are now needed to describe and monitor changes of athlete's gait pattern through an entire championship year and if possible from the beginning of the athlete's musculoskeletal development, starting at football academies, school and college. Usage of the described system by the medical staff of a soccer team is easy and recording and gathering of athlete's data can be made in everyday practice. The ability to acquire follow-up data on gait characteristics for each individual might also be of great importance in training and overall soccer performance planning. Furthermore, it could provide a reliable procedure for objectively observing the development of gait variability as a young athlete grows up. A clinically useful future goal could be the assessment of susceptibility of an athlete to sport injuries by a simple gait measurement.

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6. References

Agre J.C., Baxter T.L., Musculoskeletal profile of male collegiate soccer players, Arch Phys Med Rehabil, 1987, 68(3):147-50.

Arif M., Othaki Y., Nagatomi R., Ishihara T. and Inooka H., Analysis of the effect of fatigue on walking gait stability, Proc of Int Symp on Micromechatronics and Human Science IEEE, 2002, 253–258.

Arif M., Othaki Y., Nagatomi R., Ishihara T., Inooka H., Estimation of the effect of cadence on gait stability in young and elderly people using approximate entropy technique, Meas Sci Rev, 2004, 4(2): 29–44.

Auvinet B., Chaleil D., Barrey E., Accelerometric gait analysis for use in hospital outpatients, Rev Rhum Engl Ed, 1999, 66(7-9):389-397.

Chen K.Y., Basset D.R. Jr., The technology of accelerometry-based activity monitors: current and future, Med Sci Sports Exerc, 2005, 37(11 suppl):S490-S500.

Culhane K.M., O'Connor M., Lyons D., Lyons G.M., Accelerometers in rehabilitation medicine for older adults, Age and Ageing, 2005, 34:556-560.

Denegar C.R., Fraser M., How useful are physical examination procedures? Understanding and applying likelihood ratios, J Athl Train, 2006, 41(2):201-206.

Korhonen M.T., Suominen H., Viitasalo J.T., Liikavainio T., Alen M., Mero A.A., Variability and symmetry of force platform variables in maximum-speed running in young and older athletes, J Appl Biomech, 2010, 26(3):357-66.

Lee J.B., Sutter K.J., Askew C.D., Burkett B.J., Identifying symmetry in running gait using a single inertial sensor, J Sci Med Sport, 2010, 13(5):559-63.

Mathie M.J., Coster A.C., Lovell N.H., Celler B.G., Accelerometry: Providing an integrated, practical method for long-term, ambulatory monitoring of human movement, Physiol Meas, 2004, 25(2):R1-R20.

Moe-Nilssen R, Helbostad JL. Estimation of gait cycle characteristics by trunk accelerometry. J Biomech 2004; 37(1):121-126.

Papadakis N., Christakis D., Tzagarakis G., Chlouverakis G., Kampanis N., Stergiopoulos K., Katonis P., Gait variability measurements in lumbar spinal stenosis patients. Part A: Comparison with healthy subjects, Physiol Meas, 2009, 30:1171-1186.

Papadakis N., Christakis D., Tzagarakis G., Chlouverakis G., Kampanis N., Stergiopoulos K., Katonis P., Gait variability measurements in lumbar spinal stenosis patients. Part B: preoperative vs postoperative gait variability, Physiol Meas, 2009, 30:1187-1195.

Puers R., Catrysse M., Vandevoorde G., Collier R.J., Louridas E., Burny F., Donkerwolcke M., Moulart F., A telemetry system for the detection of hip prosthesis loosening by vibration analysis, Sensors Actuators A: Physical, 2008, 85(1-3):42-47.

Shannon C.E., A Mathematical Theory of Communication, The Bell System Technical J., 1948, 27, 379-423 and 623-656.

Tononi G., Edelman G., Sporns O., Complexity and coherency: integrating information in the brain, Trends Cogn Sci, 1998, 2(12):474–484.

Tsivgoulis S.D., Tzagarakis G.N., Papagelopoulos P.J., Koulalis D., Sakellariou V.I., Kampanis N.A., Chlouverakis G.I., Alpantaki K.I., Nikolaou P.K. and Katonis P.G., Preoperative versus postoperative gait variability of acute Anterior Cruciate Ligament deficiency, J Int Med Res, 2011, 39(2): 580-93.

Tzagarakis G.N., Tsivgoulis S.D., Papagelopoulos P.J., Mastrokalos D.S., Papadakis N.C., Kampanis N.A., Kontakis G.M., Nikolaou P.K., Katonis P.G., Influence of acute ACL deficiency in gait variability, J Int Med Res, 2010, 38(2):511-25.