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A METHOD FOR THE ANALYSIS OF THE FREE MOMENT'S VARIABILITY: A CASE STUDY

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The variability of the biomechanical parameters is considered a predictor of falling risk. The causes of this variability are intrinsic (normal variations, presence of a pathology and aging effect) or extrinsic (the evaluating methodology, variation of environmental conditions, etc.). The free moment represents the vertical moment applied in the center of pressure and is considered to be sensitive to the movement and the imbalances of the whole body in the transversal plane. Based on a case study, a knee surgical intervention, the article presents a method for determining the variability of the free moment using the coefficient of variation for different time intervals of the stance phase. The main results of our study indicate a different magnitude of the variability of the free moment for one lower limb compared with the other one, the variability of the free moment for the operated knee being smaller, with values between 15,8 – 65,6 %. The smaller values of the variability for the operated knee joint reflect a more challenging situation from a functional point of view, generated by this joint. Evaluating the variability of the free moment in time could be a useful tool for the progress of the rehabilitation period.

Key words: free moment, variability, method.

INTRODUCTION

The variability of the biomechanical parameters represents the intrinsic or extrinsic registered variation of the values of the kinematic, spatio-temporal, kinetic or electromyographic parameters[1]. The variability of the biomechanical parameters specific to different types of activities has as intrinsic causes: normal variations, presence of pathology, aging effect. The extrinsic causes are the evaluating methodology, variation of environmental conditions, etc. According to the reviewed literature, the variability of the biomechanical parameters is a better predictor of the falling risks compared with the average values of the same parameters[2]. The kinematic parameters have a low variability, meanwhile the variability of the kinetic parameters is increased as an expression of the adaptability needed to adjust the body control to more challenging conditions[2,3]. Biomechanical parameters such as the excursion of the center of pressure, Cop, cadence, walking speed were studied from the perspective of predicting falling risks. At the same time, the variability was used to evaluate the efficiency of the medical devices in the conservative treatment of lower limbs, McPoil et al. obtaining a high variability of the center of pressure pattern integral and suggesting that this parameter cannot be used for the evaluation of the foot orthotic efficiency[4]. As a measure of the variability, standard deviation or coefficient of variation is used. The variability could be calculated in specific moments of the gait cycle or for time intervals corresponding to different tasks in the different phases of gait.

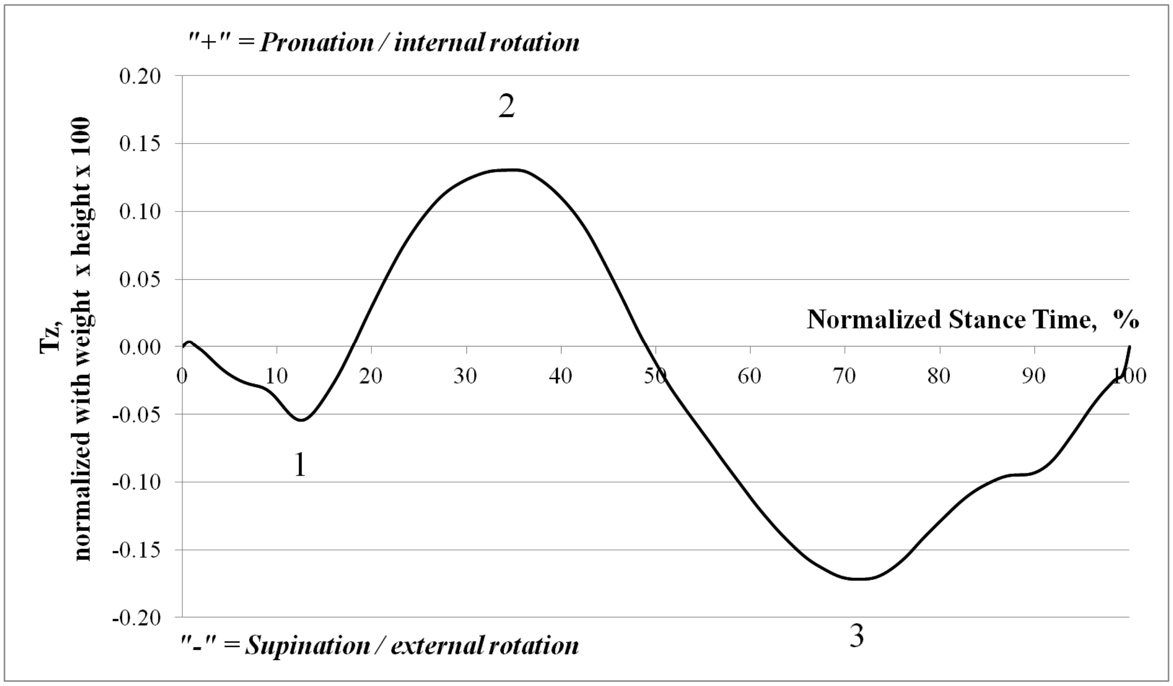

Fig. 1. Free moment graph – important landmarks.

In the last case, the variability is calculated for a representative average curve of the parameter of the interest determined based on a set of different trials.

In our case study, we have analysed a method for calculating the variability of the free moment, noted Tz or Mz', as this parameter is considered to be sensitive to the movement and the imbalances of the whole body angular momentum in the transversal plane, being an expression of the torsional loading during the gait cycle or a predictor of tibial fractures in sports activities[5-8]. Free moment is a measure of the dynamic posture as an increased value of its peaks represents the higher effort made by the body in order to keep the body's center of gravity close to the middle of support base during single stance phase of walking[9]. The free moment represents the vertical moment applied in the center of pressure. It is measured with a force platform, being a function of ground reaction force components, moments and position of center of pressure, in a specific moment:

$$T_z = M_z - Fy(X_{PWA}) + Fx(Y_{PWA})$$

$$Xpwa = \frac{FxMz - FzMy}{F^2} - \frac{Fx^2My - FxFyMx}{F^2Fz}$$

$$Ypwa = \frac{FzMx - FxMz}{F^2} - \frac{FxFyMy - Fy^2Mx}{F^2Fz}$$

where:

– F_x, F_y, F_z represents the components of the ground reaction force,

– M_x, M_y, M_z represents the moments in the center of force platform,

– x_{pwa} si y_{pwa} represents the coordinates of the point of wrench application .

Generally, as the horizontal forces have smaller values and their contribution to the calculation of the center of pressure are neglected[10]. When the influence of horizontal forces and moments is taken into consideration, the center of pressure is known as the point of wrench application. In our present study we have used the free moment formula which takes into consideration the point of wrench application[11]. For this purpose we have used the open-source motion analyzer software named Mokka[12].

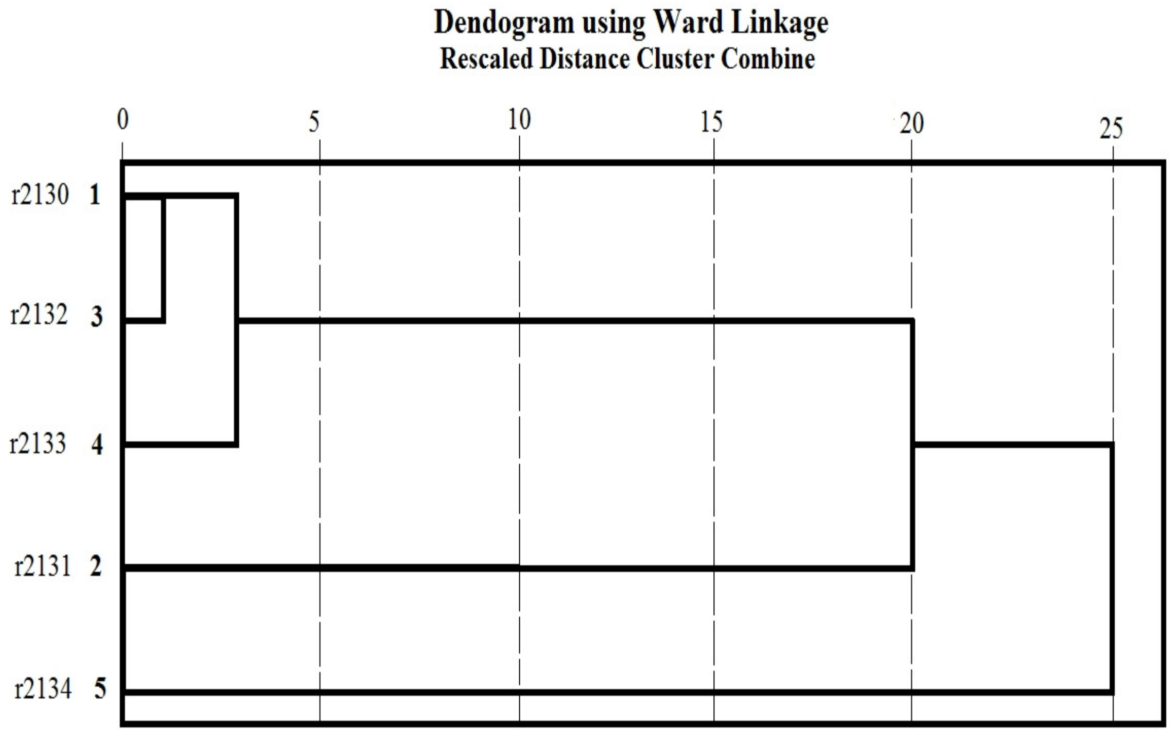

Fig.2. Cluster analysis for the selection of the representative trials.

According to the literature, the normal graph of the free moment presents 3 specific areas having a clear signification from the functional point of view of lower limb tasks (Figure 1)[7]:

– in the first interval, marked "1" on the figure no.1, coresponding to the initial contact of gait cycle, the free moment is opposite to the external rotation movement of the lower limb. This is corresponding to the supination position of the subtalar joint and locking of the knee joint necessary for assuring a safe contact of the lower limb with the support surface,

– as the subtalar joint is pronating, knee joint unlocks and lower limb internally rotates, the curvature of the free moment graph is modified according to a movement in opposition to the internal rotation of the lower limb (point no."2" in figure 1). In this phase the normal mechanisms of the body for shock absorption and accomodation with the iregularities of the supporting surface takes place,

– assuring the stability through single leg support phase (midstance and terminal phase) is imposing for the subtalar joint to supinate, knee joint to lock and lower limb to externally rotate. The coresponding free moment will be opposite to the externally rotation of the lower lomb – point no. "3" in Figure 1.

Generally the peak corresponding to the maximum internal rotation – point no. 2 – is smaller than the peak corresponding to the external rotation –point no. 3[7], reflecting the normal shock absorbing or stiffening mechanisms of the lower limb.

A stiff lower limb could be reflected in higher values of the peak corresponding to the internal rotation of the lower limb. In the reviewed literature we did not find normative data regarding the free moment as a function of age.

MATERIAL AND METHOD

In the present case study, a patient (female, age 54, height 1.63 meters, average BMI=20.6, normal feet – foot posture index, FPI = 1 for both feet[13]) of the Surgery Department of "Elias" University Emergency Hospital from Bucharest has agreed to take part in 4 measurement sessions. Nine months before starting our case study, the patient has undergone a total knee arthroplasty surgery at the left knee, being now in the phase in which the same surgical intervention has to be done on the right knee.

The approval of the institute's management for performing biomechanical measurement was obtained and the patient has signed a written consent.

For the evaluation of ground reaction force and free moment, an AMTI AccuGait force platform was used. The data were collected at a frequency of 200 Hz.

The measurement sessions and the corresponding patient's weight were as follows:

– session no.1, S_1 – preoperatively, weight: 547.6 Nwts.,

– session no.2, S_2–postoperatively, after 6 days, weight: 533.6 Nwts.,

– session no.3, S_3– postoperatively, after 6 weeks, weight: 520.6 Nwts.,

– session no.4, S_4– postoperatively, after 8 months, weight: 539.2 Nwts.,

Before each session, the subject has had enough time allocated in order to perform several practice walking trials on the force platform, at a self-selected comfortable speed according to the health status. Five correct trials per each foot in each session were collected[5, 6]. A correct trial is defined as the trial where the patient's entire footprint of one foot makes contact with the active surface of the force platform. In total, a number of 40 walking trials for both lower limbs in all measurement sessions were collected. Prior to the extraction of the variables of interest, a procedure to eliminate the mean amplitude displacement from zero was applied. In order to compensate for the aberrant values resulting from division by zero and small values of the vertical force, the beginning and ending of stance phase for each trial were determined using a threshold calculated as 10% of maximum vertical force. The ground reaction force components were normalized with the weight corresponding to the each measurement session. The free moment data were normalized with the product of weight × subject's height[5] and the results were multiplied by 100. Kinetic data were filtered using a 2nd order, zero phase shift, low pass Butterworth filter with a cut-off frequency of 6 Hz[5]. The filtered signal of the kinetic variables was normalized as a function of the stance time duration to 250 points, using a special Excel Worksheet (Microsoft Excel 10, Microsoft Corporation) having incorporated Cubic Spline and linear interpolation functions add-in and designed for the calculation of the variability of the data for different periods of time from the stance phase of the gait cycle.

An important step in calculating the variability of the biomechanical parameter was to obtain the representative average curves of the kinetic parameters (force and moment) specific to a measurement session. In order to obtain the representative average curve, a cluster analysis was performed using squared Euclidian distance as distance measure, Z-scores standardization method and cluster extraction Ward algorithm[14, 15].

IBM SPSS statistic software, version 19 (SPSS Inc and IBM Company) was used. A typical dendrogram resulting from application of the Ward algorithm is presented in Figure 2. Generally, the obtained clusters for all measurement sessions present a similar appearance, with 3 trials having the smallest rescaled distance cluster forming a clear group. Based on the literature, as the criteria used for assessing the representatives of a cluster for patient gait, the Intraclass Correlation Coefficient, single measure ICC (1,1) was chosen[14,15].

The ICC(1,1) values can range between 0 and 1, the healthy subject's gait being considered reproducible when a cluster is formed by minimum 4 curves having the value of ICC(1,1) greater than 0.95. In our study, we have considered the values of ICC > 0.90 being excellent; 0.80 < ICC <0.90 very good; 0.70 < ICC < 0.80 = good; 0.60 < ICC < 0.70 fair and ICC < 0.60 = poor[16]. It must be mentioned that for selecting the representative curves for the pathologies with great variability of gait curves, as for example in the case of parkinsonian patients, Duhamel[15] has proposed the use of functional data analysis, supplementary to the ICC.

Because of the limited numbers of trials (5 trials), registered in our measurement sessions, we have arbitrarily chosen a minimum of 3 curves to form a cluster. The ICC was calculated initially for all five trials and the procedure for improving its value has implied the one by one exclusion of the 2 trials which have produced the higher increase of the rescaled distance cluster. After each elimination, the ICC(1,1) was calculated for the remaining number of curves. The final cluster was formed by the curves which have produced the higher values for ICC. A representative average curve of the final cluster was calculated based on its constitutive gait curves.

The variability of the ground reaction force components and free moment for the final cluster, were calculated, using the Winter formula:

$$\text{CvW} = \frac{\sqrt{\frac{1}{N}\Sigma_{i=1}^{N}\sigma_i^2}}{\frac{1}{N}\Sigma_{i=1}^{N}\left|X_i\right|}\times 100$$

where the numerator is the standard deviation and the denominator is the sample mean of the representative average curve of the final cluster, N is number of normalization points for the considered time period[1,2]. The variability of the selected kinetic parameters was calculated for the entire stance phase and fortwo periods of time of interest as defined by Perry[17]: loading response and single leg support (midstance and terminal stance). The subphase timing was identified for each representative average curves based on the graph of the vertical component of the ground reaction force[17].

Table 1

Stance time, St and average velocity of Cop for each foot and each measurement session, S_1-S_4

Session	St, sec		VCop, cm/sec	
	Left	Right	Left	Right
S_1	0.813	0.882	26.64	27.99
S_2	0.987	1.006	23.88	25.64
S_3	0.910	0.870	29.84	28.62
S_4	0.878	0.833	27.34	25.29

S_1 – preoperatively, S_2 – postoperatively, S_3 – after 6 weeks, postoperatively,
S_4 – after 8 months, postoperatively

Table 2

The single and average ICC(1,1) corresponding to each final cluster

Session	Single measure		Average measure	
	Left	Right	Left	Right
S_1	0.529[5]	0.960[1]	0.771[3]	0.986[1]
S_2	0.899[2]	0.884[2]	0.964[1]	0.968[1]
S_3	0.725[3]	0.934[1]	0.913[1]	0.977[1]
S_4	0.706[3]	0.974[1]	0.878[2]	0.991[1]

[1] – excellent; [2] – very good; [3] – good; [4] – fair; [5] – poor

Table 3

Vertical force, Fz, variability (%) calculated for different intervals of time of interest, P_1-P_3, and for each measurement session, S_1-S_4

	S_1		S_2		S_3		S_4	
	L	R	L	R	L	R	L	R
P_1	17	26	30	28	27	30	28	16
P_2	10	12	14	14	12	9	11	9
P_3	14	17	19	20	19	19	17	12

P_1 = loading response, P_2 = single limb support [midstance + terminal stance], P_3 = stance phase L = left foot; R = right foot

Table 4

Free moment, Tz variability (%) calculated for different intervals of time of interest, P_1-P_3, and for each measurement session, S_1-S_4

	S_1		S_2		S_3		S_4	
	L	R	L	R	L	R	L	R
P_1	339	65	241	219	199	124	237	91
P_2	305	174	142	152	259	169	242	124
P_3	364	125	183	154	244	136	248	125

RESULTS AND DISCUSSIONS

The stance time duration (St, sec) and the average velocity of the center of pressure (Vcop, cm/s) measured by the AMTI force platform for the clusters corresponding to the each measurement sessions are presented in the Table 1. According to the literature, the average velocity of the Cop is a better estimator of the walking speed than contact time[18]. As in the majority of walking trials, the influence of the horizontal forces and moment is negligible, the AMTI force platform calculates the value of center of pressure and not the value point of wrench application.

The calculated ICC(1,1), single and average measure, corresponding to each final cluster is reported in the Table 2.

With only one exception – left foot, preoperatively (S_1) – for which the final cluster has a poor value of ICC, the remaining clusters have good to excellent ICC single measure values.

The representative curve average for the free moment corresponding to each measurement session and each foot, is represented in the Figures 3 (left foot) and 4 (right foot).

The coefficient of variation calculated for the entire stance phase according to the Winter's formula, CvW, is noted on the Figures 3 and 4 for each of the measurement sessions.

The results for the variability (%) of the vertical force, Fz, and free moment, Tz, calculated for different intervals of time of interest, P_1-P_3, and for each measurement session, S_1-S_4, are presented in the Table 3 and 4, respectively.

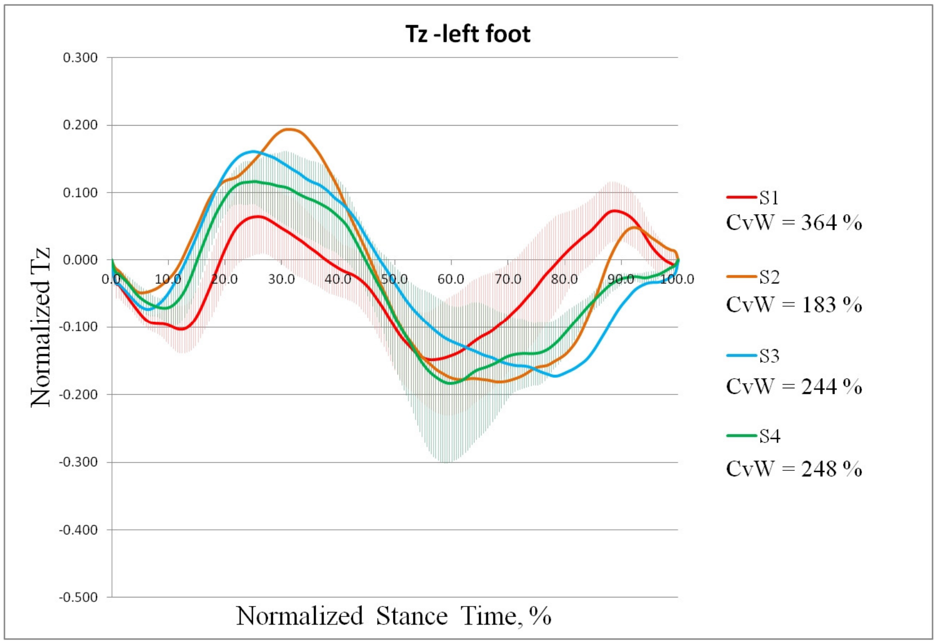

Fig.3. Free moment Tz and coefficient of variation (Winter) for all measurement sessions, left foot*.

*for the clarity of graph representation, only the average free moment curves of S1 and S2 were represented with ±1 σ_d

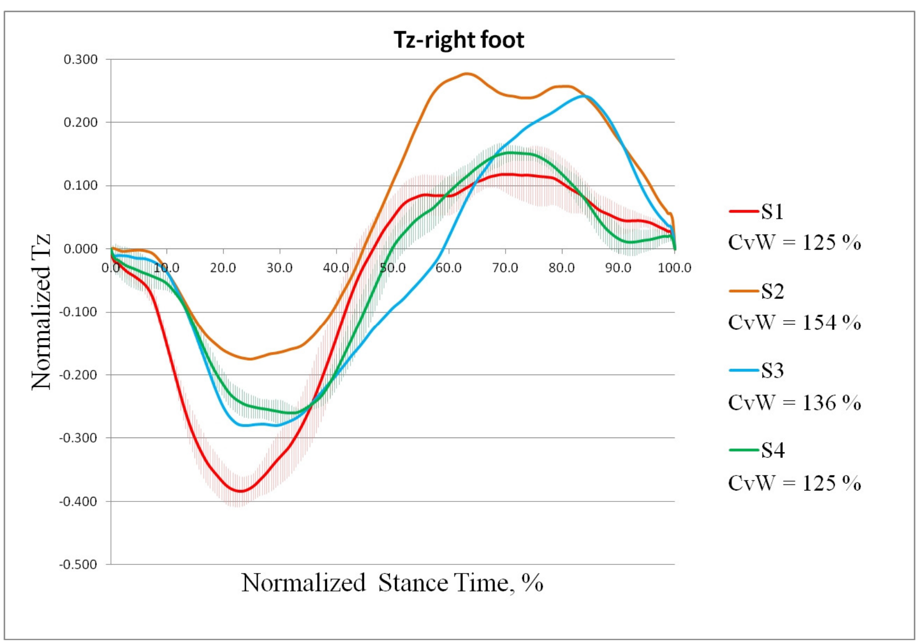

Fig.4. Free moment Tz and coefficient of variation (Winter) for all measurement sessions, right foot*.

*-see the note on Figure 3

The variability of the free moment was much higher than that of vertical force (65–364% for Tz *vs*. 9–30% for Fz), indicating a greater sensitivity of the Tz compared with Fz.

According to the reviewed literature, the free moment's variability was evaluated through different methods:

–intra- and inter-subject variability was determined by calculating the average standard deviation of distinct free moment values in specific points of the stance phase[8]. Inter-subject variability was almost 3 times higher than intra-subject variability. Intra-subject variability calculated using this method is considerably lower than inter-subject variability and it was used for running types classification through free moment pattern;

– variability to signal ratio, VSR, defined as

$$\mathrm{VSR} = \frac{\Sigma_{i=1}^{N}\sigma_i^2}{\Sigma_{i=1}^{N}\mu_i^2}$$

and representing the intra-population variability, where N is the number of normalization points for the stance time period, μ_i = the average force at each point, σ_i the corresponding standard deviation[19]. The VSR were evaluated for two groups of subjects (deficient anterior cruciate ligament, and uninjured) and four conditions (free walk, fast walk, standard pivot and cross-over pivot), the obtained values being in the range 7.7–76.7% for pivoting tasks and between 82.2–103.3 % for walking tasks. The lower variability obtained for both pivoting conditions for the injured group of subjects compared with that of the uninjured group was interpreted as a supplementary effort made by injured subjects in performing functional tasks which are challenging for the knee stability[19];

– values of the variability calculated with the Winter's formula for the coefficient of variation are reported in the reviewed literature between 8–72 % for angular displacement data and between 24–140 % for moment of force data and between 51–129 % for power generated/absorbed data[2]. Data reported refers to different kinematic and kinetic parameters calculated for ankle, knee and hip joints, and also for different groups of subjects.

As the knee joint has different tasks over the gait cycle, in the present study the variability was evaluated separately for both feet for the entire stance phase of the gait, and also for selected period of the stance phase. The main results of our study indicate a different magnitude of the variability of the free moment of one lower limb compared with the other one. The variability of the free moment for the left foot was higher than that of the right one, with values between 49.6–65.6 % for the sessions S_1, S_3 and S_4 and 15.8% for S_2. Taking into account the conclusion of the study by Hassan *et al.*[15], we can assume that operated knee joint is more challenging from a functional point of view that the other one. This can be seen on the Figure 4, where, in the time period of 0–10% from the stance phase, the Tz corresponding to the right side does not reflect a stiffening of the lower limb necessary in the initial contact phase of walking. We can observe that the variability of the right free moment is lower than the left one for the entire period of 8 months considered in this case study.

The obtained variability values came into contradiction with both clinical scores (knee and functional) as they were registered in the patient's hospital visits through Knee Scoring System[20], which indicates high and almost equally scores for both knees (Table 5). As the patient has reported 2 falls at home, between S_3 and S_4, this may lead to the conclusion that calculating the variability of the free moment could be a more realistic indicator of the functionality of both knees after a surgical intervention than the clinical scoring system.

As the results of a case study cannot be generalized, a much more systematic approach of the potential of using the force platform measurement in the case of knee surgical intervention needs to be taken into consideration.

CONCLUSIONS AND FUTURE PROSPECTS

The method of study of a kinetic parameters variability presented in this study is based on the representative average curve determined based on a cluster analysis and Intra-class Correlation Coefficient, ICC(1,1), as supplementary criteria;

– if the medical condition allows, a number of trials per session greater than five could be indicated in order to be sure that a cluster will be formed by a minimum of 4 representative curves based on excellent values of ICC;

– different values of Tz variability were obtained for left foot compared with the right one. This could reflect an imbalance produced at the level of lower limbs;

– smaller values of variability associated with functional interpretation of the representative average curve of a cluster could confirm the conclusion of previous studies regarding the link between the small variability of a kinetic parameter and more challenging tasks of the implied lower limb;

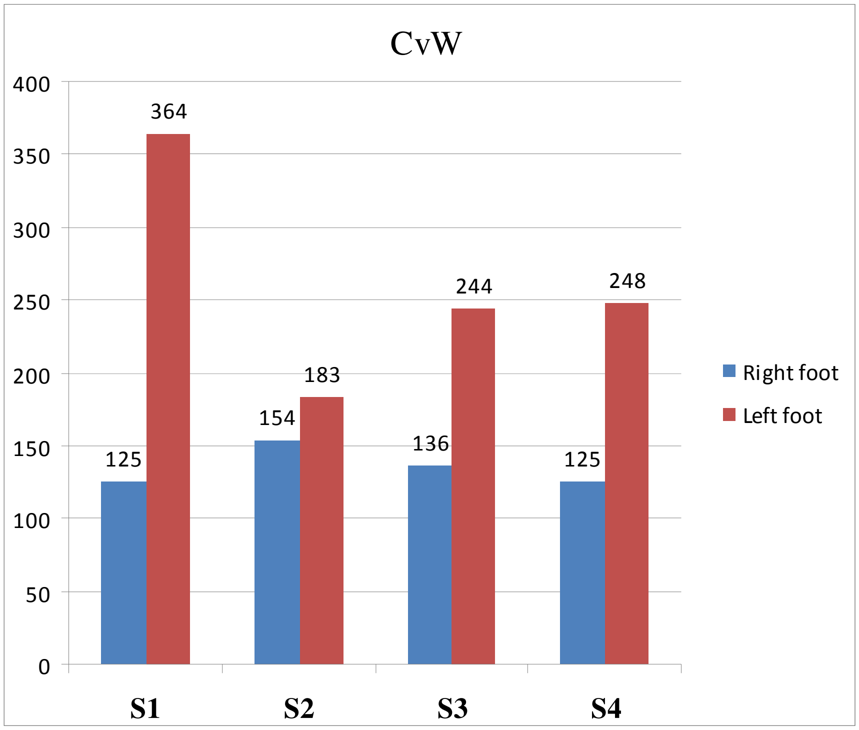

Fig. 5. The variablity (%) expressed through the coefficient of variation for the entire stance phase for left and right foot.

Table.5

The results of 2011 Knee Society Knee Scoring System

Condition	Knee score		Functional score	
	Left	Right	Left	Right
Preoperatively	-	17	-	35
Postoperatively, PO	25	-	50	-
6 weeks PO	-	93	-	90
5 monthsPO	89	-	90	-
8 months PO	-	93	-	90
10 months PO	90	-	90	-

– the variability of the free moment is much higher than that of the vertical force, Fz, which could indicate a greater sensitivity of this kinetic parameter;

– walking speed should be considered as supplementary criterion for selecting the representative curves;

– as our study is a case study, the results cannot be generalized.

LIMITATIONS OF THE STUDY

– The CvW were calculated without eliminating outliers, which could result in higher values of the CvW[1]. Free moment patterns for walking of normal and total knee arthroplasty population have to be evaluated in order to be able to make comparisons,

– the difference in the average speed of the Cop was not taken into consideration in the selection of the representative curves for the free moment. As they vary between 8.4–19.9%, it could influence the peak of kinetic parameters, being a source of errors. The postoperative Vcop (S_2) was smaller than the preoperative one–S_1 (10.3% – left foot and 8.4% for the right foot). The Vcop has varied by maximum 19.9% for the left foot and by maximum 11.6% for the right foot for all measurement sessions. The problem of the walking speed differences between different conditions (normal *vs*. pathological) or groups of patients (injured *vs*. uninjured) needs special attention in interpreting the data resulting from biomechanical studies[21].

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