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ORIGINAL ARTICLE

Effects of sensor, trials and knee joint variables on electrogoniometric gait recordings

Efeitos das variáveis sensor, coleta e articulação do joelho nos registros eletrogoniométricos da marcha

Carnaz L[1], Oliveira AB[1], Sato TO[1], Hansson G-A[2], Coury HJCG[1]

Abstract

Introduction: Different sources of variations, such as electrogoniometer characteristics and procedures, may affect the accuracy and precision of movement measurements during gait. **Objective:** To quantify the variations and compare the effects produced by different sources of variation in electrogoniometric gait recordings: the sensors, procedures (trials) and the knee joint. **Methods:** Knee flexion/extension and valgus/varus movements were recorded during gait on the treadmill. The recordings were partitioned into strides and normalized in time using a routine developed in MatLab. Mean curves for the knee during gait were derived from 50 strides, and seven conditions were evaluated: one comparing pairs of sensors; two comparing pairs of different trials (including variations due to sensors); and four comparing the right and left knees (including variations due to sensors and trials). Mean standard deviations of the differences were calculated. To estimate the variations relating to the trial and the knee joint, the compound standard deviations were transformed into variances and split into their components. **Results:** The variation introduced by pairs of sensors in the same model applied in one trial was smaller than the variation introduced by the same sensor used in two consecutive trials. Furthermore, the variation introduced by the difference between the right and left knees was greater than the variation introduced by the difference between sensors (A and B) and trials (1 and 2). **Conclusions:** It is, therefore, preferable to use different sensors in the same data recording (simultaneous) than use the same sensor in two different recordings (consecutive).

Key words: movement; measurement error; gait.

Resumo

Introdução: Diferentes fontes de variação, tais como características do eletrogoniômetro e procedimentos podem afetar a acurácia e precisão das medidas do movimento durante a marcha. **Objetivo:** Quantificar a variação e comparar o efeito das diferentes fontes de variação nos registros eletrogoniométricos da marcha: os sensores, os procedimentos (coletas consecutivas) e a articulação do joelho. **Métodos:** Movimentos de flexo-extensão e valgo-varo do joelho foram registrados durante a caminhada na esteira. Os registros foram divididos em passadas e normalizados no tempo usando uma rotina desenvolvida em MatLab. As curvas médias do joelho durante a marcha foram derivadas de 50 passadas, e sete condições foram avaliadas: uma para comparar dois sensores; duas para comparar duas diferentes coletas (incluindo a variação do sensor), e quatro para comparar os joelhos direito e esquerdo (incluindo a variação dos sensores e coletas). Os desvios-padrão médios das diferenças foram calculados. Para estimar as variações devido às coletas e à articulação do joelho, os desvios-padrão compostos foram transformados em variâncias e seus componentes isolados. **Resultados:** A variação introduzida por dois sensores do mesmo modelo aplicados em uma coleta foi menor do que a variação introduzida pelo mesmo sensor usado em duas coletas consecutivas. Ainda, a variação introduzida pela diferença entre os joelhos direito e esquerdo foi maior do que a variação introduzida pela diferença entre os sensores (A e B) e as coletas (1 e 2). **Conclusões:** Assim, é preferível usar diferentes sensores na mesma coleta de dados (simultânea) do que usar o mesmo sensor em dois registros diferentes (consecutivos).

Palavras-chave: movimento; erro de medida; marcha.

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Introduction

Physical therapists require quantitative, reliable and precise methods of evaluating impairments, disabilities and handicaps and also determining rehabilitation outcomes. Because of the feasibility of flexible electrogoniometers, they have been used to record functional movements[1-6]. However, different sources of variation can affect the accuracy and precision of the measurements, such as the different characteristics of particular goniometers, misalignment of the endblocks relative to the planes of movement, limited reproducibility of the application of the endblocks, vague definition that might lead to imprecise recordings of the reference position[7-9] and differences between bilateral joints such as the knees during normal gait[10,11].

Several studies have analyzed the different sources of variation that can affect wrist and forearm electrogoniometric recordings[7,12]. Nevertheless, few studies have applied flexible electrogoniometers to the evaluation of gait, and none of them evaluated the sources of variation in this application.

To estimate the variation in electrogoniometric gait recordings, particularly due to sensors, procedures and knee joints, we must consider different ways to isolate each effect. One way to determine the effect of the sensors would be to record the same knee, using different sensors, in the same trial (e.g. two similar goniometers attached to each other with double-sided adhesive tape), i.e. simultaneous measurements. To evaluate the difference between right and left knee movements, data collection could be simultaneous using different sensors, or consecutive using the same sensor. Thus, it would be possible to decide whether it is preferable to use different sensors in the same data recording (simultaneous) or the same sensor in two different recordings (consecutive), in order to achieve the smallest variation.

The objective of this study was to quantify the variations and compare the effects produced by different sources of variation in electrogoniometric gait recordings: the sensors, procedures (trials) and the knee joint.

Methods

Subjects

Eight healthy males (age 21.6±3.5 years; height 170±3cm; weight 66.4±7.0kg) participated in the study. They did not present any musculoskeletal injuries, balance disorders or symptoms. Subjects presenting any lower-limb postural deviation were excluded in order to ensure that only subjects presenting symmetrical lower limbs were included. Furthermore, since electrogoniometer recordings are anthropometry-dependent, the subjects were selected within the height range of 165 to 175cm. Sixty healthy males were evaluated but only eight subjects were included because our inclusion criteria were strict and made it very difficult to find subjects. This study was developed with approval from the Ethics in Human Research Committee of Universidade Federal de São Carlos (Approval report number 035/04) and the subjects signed a consent form.

Equipment

Knee flexion/extension (F/E) and valgus/varus (V/V) movements were recorded using two biaxial flexible electrogoniometers (M110, Biometrics Ltd., Gwent, UK) and an acquisition unit (Data Logger 1001, Biometrics Ltd., Gwent, UK). The two sensors were named A and B. The sampling frequency was 1,000Hz.

Procedures

For two of the three trials, bilateral recordings of F/E and V/V were performed. One of the goniometers (A or B) was attached to the shaved lateral face of each knee with the subjects standing in anatomical position. The center of the inter-joint line was taken to be the common reference for the leg and thigh. The center of the sensor spring coincided with this line, and the endblocks were aligned over the axis of the thigh and leg, with the greater trochanter and lateral malleolus as the reference points (Figure 1). To avoid kinematic crosstalk, the aim in the alignment was to take the "true" flexion axis[13]. A single physical therapist was responsible for attaching the sensors. The area reserved for the sensors was marked out using a dermographic pen to allow precise reproduction of the attachments in the subsequent trials. The knee angles when standing were taken to be the reference position and the recordings of these angles were subtracted from the subsequent gait recordings. For the third trial, the goniometers were attached to one another using double-sided adhesive tape (Figure 1) then attached to the right knee.

Three gait trials were performed on each subject. The first trial was done with sensor A on the left knee (recording AL1)

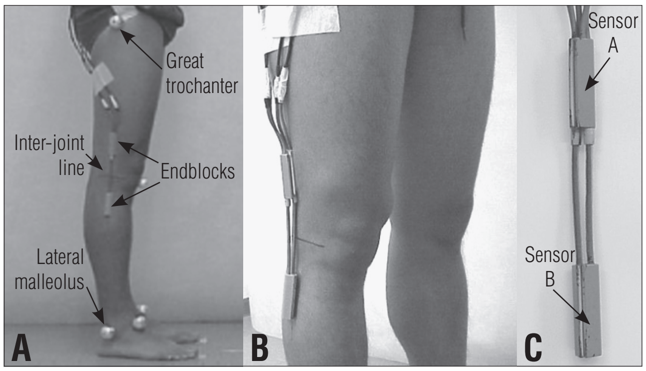

Figure 1. (A) Electrogoniometer attachment in the first and second trials; (B) and (C) Sensors A and B attached to each other, for attachment to the right knee in the third trial.

and sensor B on the right knee (BR1); the second trial was done with sensor A on the right knee (AR2) and sensor B on the left knee (BL2); and the third trial was done with both sensors (A and B) on the right knee (AR3 and BR3, respectively). The sequence of the trials was randomized between the subjects and there was a five-minute interval between trials. For each trial, after recording the reference position, the subjects were gradually familiarized with a treadmill, walking at 5km/h, and knee movements were recorded for 90 seconds.

A pilot test had been previously conducted to investigate the effects of varying the position of the goniometer. The same trained physical therapist performed palpation and attached the goniometer to the subject's knee twice. The maximum variation due to sensor replacement was 1.1° for F/E and 3.6° for V/V movements. Schwartz, Trost and Wervey[14] evaluated a similar effect and, although these authors did not show these results explicitly, it can be inferred from their graphs that they found errors ≤4° for F/E and ≤2° for V/V movements.

Data analysis

Data processing was performed using a routine developed in MatLab version 6.5 (MathWorks Inc., Natick, MA, USA). Through this routine, all the data were filtered using a low-pass, second-order, zero-lag Butterworth filter at 10Hz. The recording was partitioned into strides, which were defined as the time between two consecutive heel strikes. The heel strike was taken to be the first minimum after a maximum flexion[15]. The central 50 strides (corresponding to about 60 seconds of recording) for each knee were selected, and were normalized in time for both F/E and V/V, represented by 101 data points (one for each percent of the stride). Mean F/E and V/V curves were derived from these 50 strides, and were used for the subsequent analysis.

From these data, seven differences were calculated: one comparing sensors A and B (AR3-BR3); two measurements comparing trials 1 and 2 (including the variation due to the sensor: BR1-AR2 and AL1-BL2); and four measurements comparing the right and left knees (including the variation due to the sensor: BR1-AL1 and AR2-BL2; and the variation due to the trial: AR2-AL1 and BR1-BL2).

For each comparison described above, the mean value of the difference between the two curves for the 101 points was calculated. This value was taken to be the offset and was subtracted from each of the 101 points on one curve. Hence, any systematic shift in F/E and V/V, between the two recordings compared, was disregarded.

After offset subtraction, the mean standard deviation (SD) between the two knee curves was calculated to obtain a summary measurement of the difference, using the formula below[16].

$$SD_{mean} = \left(\frac{\sum_{i=1}^{k} SD_i^2}{k} \right)^{\frac{1}{2}}$$

where SD_{mean} is the mean of the individual point - by - point standard deviation values across all instants (k=101) that make up the curve, and SD_i is the standard deviation value for the i*th* instant.

The standard deviations obtained were used to estimate the size of the different sources of variation. Since the variations due to the sensor, trial and knee joint can be regarded as independent, their contributions to the compound variations are cumulative, provided that the variations are expressed as variances. Thus, a hierarchical analysis of variance was applied; the SDs were squared, i.e. transformed into variances, and calculated for each subject and movement (F/E and V/V), separately. The variance due to the sensor was directly extracted from the condition AR3-BR3. The variance due to the trial was derived by subtracting the variance due to the sensor from the variance due to the trial plus the sensor (BR1-AR2 and AL1-BL2), and the mean value of these two estimates was used. The variance due to the knee joint was derived by subtracting the variance due to the sensor from the variance due to the knee joint plus the sensor (BR1-AL1 and AR2-BL2), and by subtracting the variance due to the trial from the variance due to the knee joint plus the trial (AR2-AL1 and BR1-BL2); and the mean value of these four estimates was used. The SDs (i.e. the square roots of the variances) were then calculated and presented in tables and figures (Figure 2 and 3). Since the data depicted in Figure 4 did not present normal distribution, the Kruskal-Wallis test was run to evaluate the differences in F/E and V/V relating to the sensor, trial and knee joint conditions. The post-hoc Dunn test was applied when statistical differences were identified.

Results

The eight subjects and the three trials presented a mean peak amplitude of 53.3° (SD=1.5°) for F/E, with a mean peak flexion of 56.2° (1.6°) and mean peak extension of 2.9° (1.3°). The V/V movements were smaller: mean peak amplitude of 12.0° (1.7°), mean peak valgus of 9.5° (2.7°) and mean peak varus of -2.5° (1.5°). The flexion and valgus peaks were reached during the swing phase, and the extension and varus peaks occurred during the stance phase.

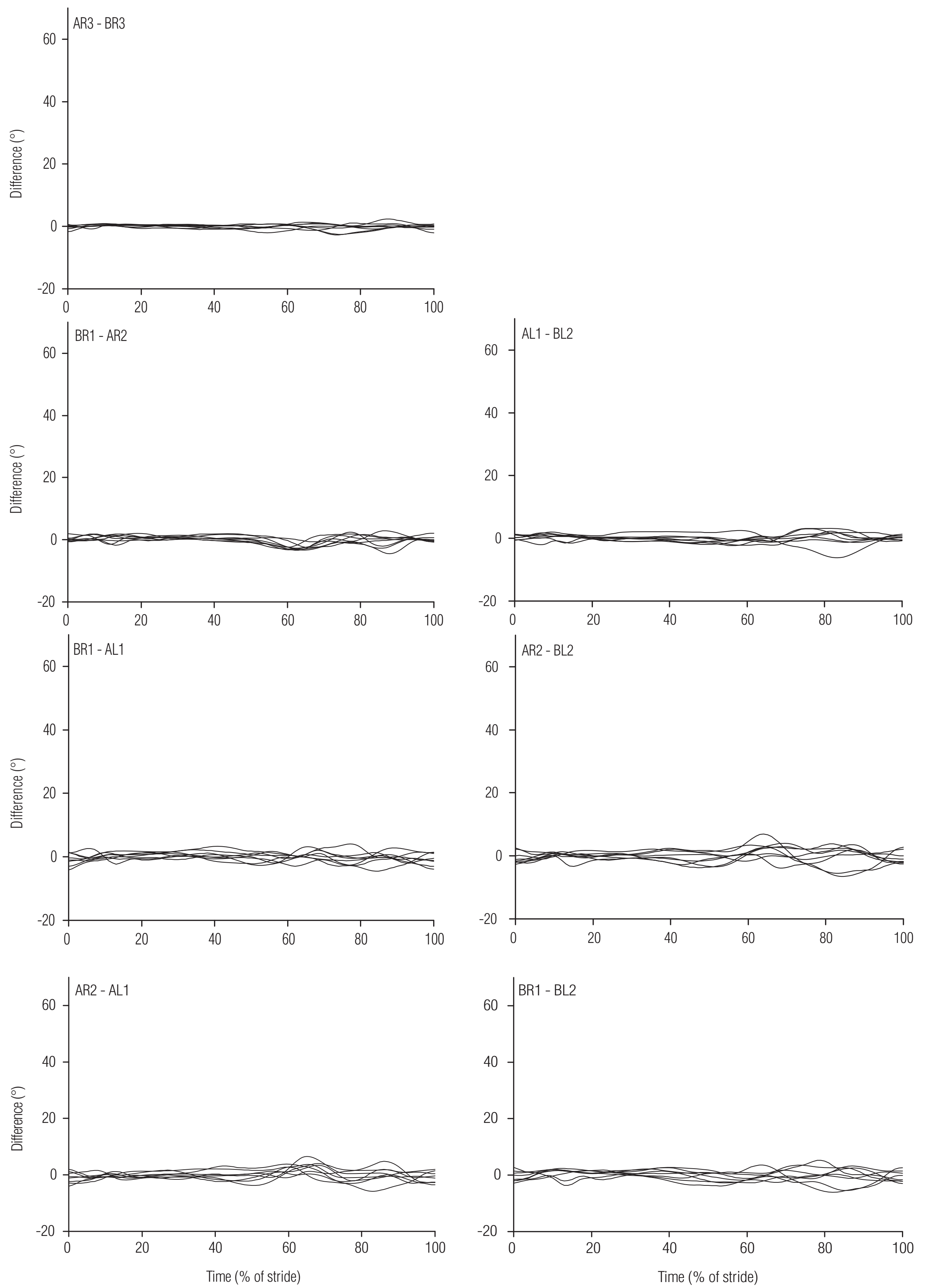

Figure 2. Difference curve graphs for all subjects in regards to each comparison of knee flexion-extension during gait.

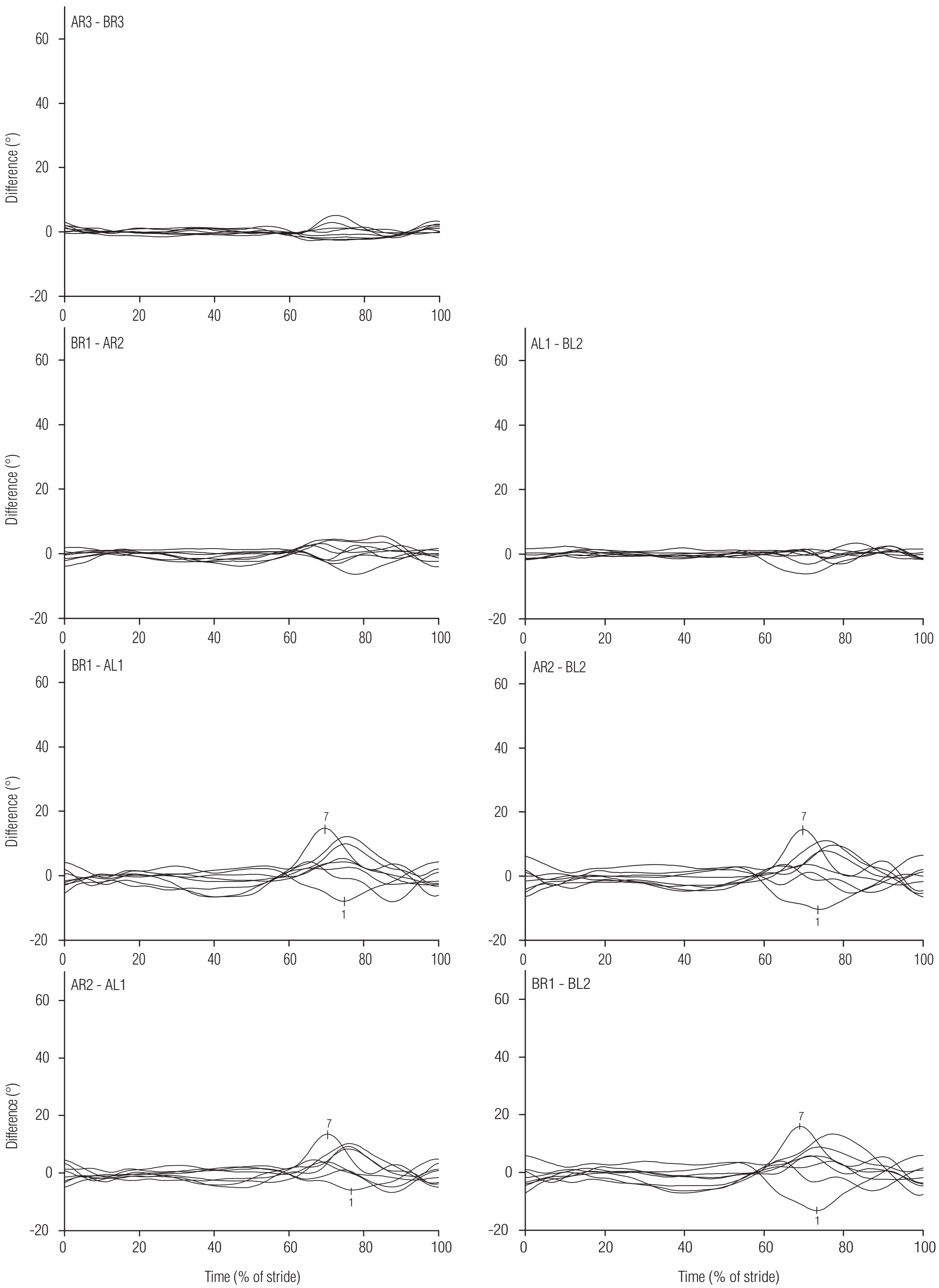

Figure 3. Difference curve graphs for all subjects, in regards to each comparison of knee valgus-varus during gait. In the knee joint comparisons (knee joint plus sensor and knee joint plus trial), it can be seen that subjects 1 and 7 presented marked differences.

Figures 2 and 3 show the difference curves, for each subject and comparison. For all comparisons, the variation was generally higher for V/V than for F/E. For both F/E and V/V, and for all comparisons, the differences were more pronounced during the swing phase, i.e. 60 to 100% of stride. Sensor comparisons (AR3-BR3) for both F/E and V/V movements presented smaller deviations from zero values, and the knee curves (plus sensor and plus trial) showed larger deviations from zero, especially for V/V movements. Some subjects showed a difference between the knee joints, which, for all combinations of knee joint plus trial and knee joint plus sensor, was obvious in the graphs. For example, Figure 3 shows that, at the beginning of the swing phase (at about 70% of stride), the valgus angle for the right knee is about 15° greater than for the left knee for subject 7. A difference of similar size, but in the reverse direction and somewhat later in the swing phase, can be seen for subject 1.

All sources of variation, presented as SDs, are plotted in Figure 4. In general, the sensors represented the smallest source of variation for both F/E and V/V. Variation due to the trial showed values with greater fluctuation than did the variation due to the sensor. For F/E, these variations were roughly at the same level, while for V/V, the variation due to the trial was smaller than the variation due to the sensor, for most of the subjects. As expected, the variation due to the trial plus the sensor was greater than the variation due to either the sensor or the trial alone, except for a few instances caused by random effects. The variations due to knee joints presented higher values, and these were generally considerably higher for V/V than for F/E. Of course, the combined variations (knee joint plus sensor and knee joint plus trial) were greater than the knee joint variations alone. However, these differences were small, especially for V/V, i.e. the relative influence of sensor and trial on the recording of the knee joint variation was small.

Table 1 shows that, for F/E, the variation due to the sensor was smaller than the variation due to the trial (statistically non-significant), while the variation due to the knee joint was greater than the variation due to the trial, and significantly greater than the variation due to the sensor ($p<0.05$). For V/V, the variation due to the trial showed the smallest value and the variation due to the knee joint was significantly greater than the variation due to the sensor ($p<0.05$) and the trial ($p<0.05$).

Discussion

The knee joint variable had more influence in determining variation in the results than did the sensor and trial variables, for most of the subjects. Furthermore, the variation was much

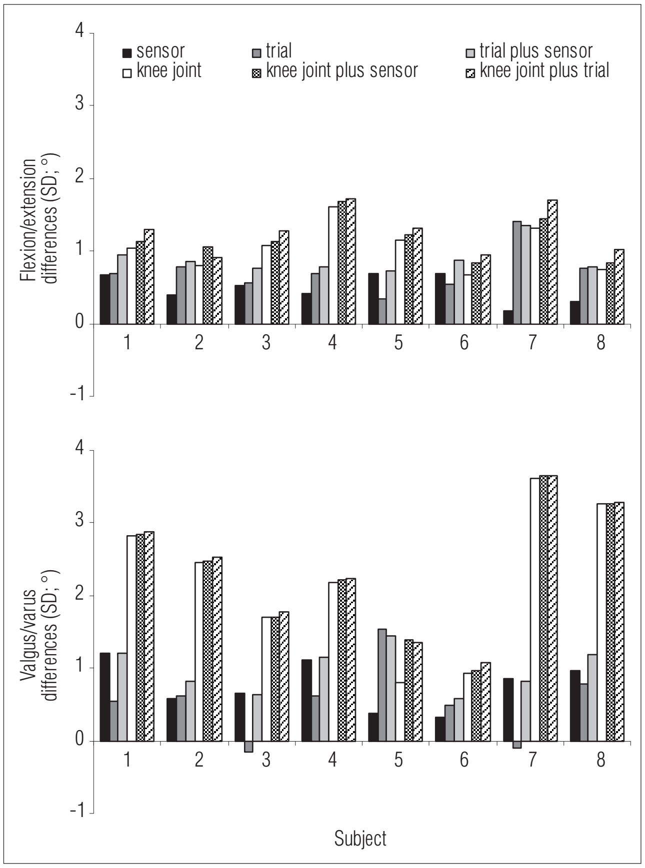

Figure 4. Compound variations (trial plus sensor, knee joint plus sensor and knee joint plus trial) and separate variations (sensor, trial and knee joint) in flexion/extension and valgus/varus for each subject (SD; °).

Table 1. Variations (standard deviation – SD;°) due to sensor, trial and knee joint. Mean values relating to eight males are shown, for both flexion/extension and valgus/varus movements. Nonparametric analysis of variance was applied, and if the results were significant ($p<0.05$), the Dunn test was applied to test for significant differences (*) between sensor, trial and knee joint.

			Sensor	Trial	Knee joint
Flexion/extension	Mean SD		0.48	0.72	1.05
	Dunn test	*sensor*	-	NS	*
		trial	NS	-	NS
Valgus/varus	Mean SD		0.76	0.54	2.22
	Dunn test	*sensor*	-	NS	*
		trial	NS	-	*

NS – statistically non-significant.

greater between the knee joints for V/V than for F/E movements. For all sources, the variation was generally greater for the swing phase than for the stance phase.

Individual sensors of the same model can produce different outcomes in a jig, where no other source of variation that would usually be present in functional situations can occur. Shiratsu and Coury[9] reported up to 3° difference between individual sensors (Biometrics Ltd.; XM150B) attached to a jig that reproduced full-range amplitudes for F/E movements and deviations. In the present study, the variations (in SD) introduced by the sensors ranged from 0.48° to 0.76°. Considering the different measurements for characterizing the differences between sensors, this is consistent with the above-mentioned study, thus indicating that this source has a small effect on knee joint measurements during gait. However, some crosstalk effect from the sensors can be expected.

Crosstalk, i.e. erroneous recordings of V/V movements during F/E movements, and vice versa, can occur for three reasons: (1) mechanical deviations in the geometrical properties of the goniometer sensing elements; (2) misalignment of one of the endblocks, resulting in axial rotation of the goniometer; or (3) mounting the goniometer outside of the principal plane of the movement. The first type of crosstalk is an inherent property (fingerprint) of the particular goniometer and is of significance only for high F/E angles. This error presumably contributes towards the difference between the sensors that is observed in the V/V movements during high flexion movements, i.e. during the swing phase. The second type of crosstalk will occur if the endblock on the shank is not aligned with the sagittal plane. In this case, pure F/E movements will cause an erroneous recording of V/V that is proportional to the F/E amplitude[7]. Prior awareness of this potential source of error was the reason for ensuring strict and careful attachment of the endblocks in the present study. However, for comparisons between the knee joints, the effect of sensor positioning cannot be disregarded. The third source of crosstalk will occur if both endblocks are misaligned in relation to the sagittal plane. If the goniometer were to be placed in the frontal plane, i.e. at the front or back of the knee (although in reality this position is practically impossible), the F/E angle would appear in the channel that would record the V/V angle if the goniometer were to be placed in the sagittal plane. Hence, placing the goniometers in any plane that is intermediate between the sagittal and frontal planes will result in crosstalk. For example, to obtain an erroneous recording of 12° of V/V with an F/E range of 56°, a misalignment of 26° of one of the endblocks is required[12].

Another source of variation is the occurrence of soft tissue artifacts due to the relative displacement between the electrogoniometer attachments and the anatomical reference points that are used to represent the joint angle in the static position[8,17,18]. Moreover, any angular differences between the endblocks will be compensated by recording a reference position (and subtracting the F/E and V/V angles from the subsequent recordings), as long as these angular differences do not change. One possibility for reducing the influence of local changes is to perform "spatial averaging" by applying a plate or ruler over the thigh and the shank[8].

The repeatability of knee movements is clearly dependent on joint stability and adaptability[19]. Moreover, as the V/V range of movement is small[20-23], it can be strongly influenced by individual anatomical and functional characteristics[24,25]. Individual characteristics, which were analyzed here as knee joint variation, introduced the highest source of variation. However, these results must be carefully interpreted, as this knee joint variation is close to the variation due to the positioning of the goniometer (as presented in the Methods section). Other different individual characteristics are considered to have an influence on gait kinematics. Among these are age and gender[26-30], which were controlled for in the present study. Furthermore, lateral dominance has been considered to have some influence on gait kinematics, although this issue still remains controversial[27,29,30].

Finally, this article has provided guidelines to identify the sources of variation in electrogoniometric recordings of the knee during gait, and has suggested methodological alternatives to isolate and correct these sources of variation.

Conclusions

The variation introduced by two separate sensors of the same model applied in one trial was smaller than the variation introduced by recording movements in two consecutive trials using the same sensor, with regard to recording knee movements during gait. Nevertheless, the variation introduced by the difference between knee joints was greater than the variations promoted by sensors and trials, and this difference was within the variation due to sensor repositioning. Thus, it is preferable to use different sensors in the same data recording (simultaneous) than to use the same sensor in two different recordings (consecutive).

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