Short communication

Estimation of the body center of mass velocity during gait of people with transfemoral amputation from force plate data integration

C. Lansade [a], X. Bonnet [b], N. Marvisi [a,b], J. Facione [d], C. Villa [b,c], H. Pillet [b,*]

[a] Institut Robert Merle D'Aubigné, Valenton, France
[b] Institut de Biomécanique Humaine Georges Charpak/Arts et Métiers, Paris, France
[c] INI/CERAH, Créteil, France
[d] HIA Percy, Clamart, France

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A B S T R A C T

Background: Body Center Of Mass velocity assessment is a prerequisite for several applications in prosthetic control and rehabilitation monitoring. Force plate data integration is a promising alternative to full-body quantitative analysis of segmental kinematics to estimate the velocity. Still, it remains to be implemented and validated for people with transfemoral amputation.
Methods: Two methods were used (force plate based and pelvic markers based) for Body Center Of Mass velocity estimation in a clinical context. The two methods were comparatively assessed on overground walking data of eight people with transfemoral amputation in a laboratory equipped with a motion capture system and force plates compared to reference estimation derived from a full body segmental gait analysis. The 'Methods' agreement with the reference was quantified from the Bland and Altman procedure.
Findings: The estimation of Body Center Of Mass velocity from force plate data integration was considered acceptable in terms of limits of agreement. In addition, the hypotheses used to determine integration constants were evaluated and shown to be reasonable as far as the walking direction is well controlled.
Interpretation: Results demonstrate the possibility to use the force plate method to assess the Body Center Of Mass velocity of people with transfemoral amputation for straight walking on level ground. An estimation from the velocity of pelvic markers can also be a relevant alternative as soon as the walking velocity remains low. Further investigation will deal with the impact of the errors on the computation of derived parameters such as individual limb power.

1. Introduction

In the context of clinical follow-up, an alternative to full body gait analysis is monitoring the Body Center of Mass (BCOM) motion.(Dauriac et al., 2019; Hof et al., 2007; Tesio and Rota, 2019) More precisely, the BCOM kinematics has been used to estimate mechanical energy changes (Tesio et al., 1998) or work(Donelan et al., 2002a) or describe symmetry.(Gard et al., 1996) Such determinants of gait revealed relevant from a clinical point of view as detailed in the work of Kuo and Donelan.(Kuo and Donelan, 2010)

To obtain BCOM velocity, the criterion standard (referred hereafter as the SEG method) differentiates the BCOM position provided by the combination of the Body Segment Inertial Parameters (BSIP) with the kinematics of the individual segments.(Pavei et al., 2017) However, this method relies on a full-body marker set for segmental kinematics assessment. In addition, it necessitates an expensive 3D motion capture camera system, which is time consuming and requires expertise inconsistent with actual clinical practice.

To overcome these limits, a method, also based on 3D motion capture, approximates the BCOM from a limited number of markers placed on the pelvis.(Whittle, 1997) This method (referred as MARK method), simplifies the acquisition by reducing the needed number of markers but implies the major assumption that BCOM does not move significantly relative to the pelvis.

Conversely, BCOM velocity can also be obtained from BCOM acceleration integration, knowing that this acceleration is directly proportional to the external force applied on the body, measured by force platforms(Adamczyk and Kuo, 2015; Donelan et al., 2002b; Whittle,

* Corresponding author at: Institut Robert Merle d'Aubigné, 2 Rue Emilion Michaut et Lucien Rabeux, 94460 Valenton, France.
E-mail addresses: c.lansade@irma-valenton.fr (C. Lansade), helene.pillet@ensam.eu (H. Pillet).

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1997) (FP method). The key issue is the determination of the constants of integration. Hypotheses have been formulated for non-amputee persons(Donelan et al., 2002b) and also used considering people with transtibial amputation(Houdijk et al., 2009) to determine these constants. However, the underlying consideration of symmetry of gait used to formulate these hypotheses is not valid anymore when considering people with transfemoral amputation due to the more pronounced step-to-step asymmetry..(Nolan et al., 2003; Prinsen et al., 2011) Consequently, there is a need to propose an adaptation of initial conditions and to test the method for this population.

In this context, this study aims to assess the validity of the forceplate (FP) method adapted for transfemoral prosthesis users by comparison to the criterion standard segmental (SEG) method.

2. Material and methods

2.1. Experimental measurements

Eight volunteers with unilateral transfemoral amputation were recruited for the experiment (Table 1). They were free from musculo-skeletal disorders on the intact side and were able to walk without walking aids. Volunteers were equipped with 59 passive reflective markers according to a protocol previously published.(Al-Abiad et al., 2020) In particular, four markers were placed on the superior iliac spines of the pelvis (anterior and posterior). Biplanar X-Ray radiographs were acquired with the EOS system(Dubousset et al., 2010) (CPP NX06036), from head to toes in a free standing position. Then, participants walked at their self-selected speed while measuring kinematics simultaneously with eight infrared cameras (VICON) at 100 Hz and ground reaction forces (GRF) with three force plates at 1000 Hz. The dimensions and positions of the force plates allow recording at least four consecutive foot-strikes on the platform. Markers position data were filtered with a 4th order Butterworth bidirectional filter with a cut-off frequency 5 Hz.

2.2. Data analysis

Motion analysis data has been post-processed using a custom-made program with Matlab software.

2.2.1. BCOM velocity from segmental method (SEG)

BSIP were computed from the body, including the residual limb shape contour reconstructed using EOS radiographs(Nérot et al., 2015) and segmented according to Dumas et al.(Dumas et al., 2007) The mass of the socket was added to one of the residual limbs. Densities were taken from Dempster,(Dempster, 1955) except for the thorax, where a modified density taken from(Amabile et al., 2016) was used. The prosthetic foot and knee "(prosthetic shank mass being neglected compared to the mass of the knee prosthetic component)" were considered as point masses located at their centre of mass.(Al-Abiad et al., 2020)

Segmental kinematics allowed the computation of the 3D instantaneous BCOM position using the estimated BSIP. Finally, the BCOM velocity was obtained with a 4th order finite difference.

2.2.2. BCOM velocity with pelvic 'markers' approximation (MARK)

The BCOM position was approximated with the midpoint between the four posterior and anterior iliac spine markers(Whittle, 1997) and differentiated with a 4th order finite difference to compute the velocity.

2.2.3. BCOM velocity using force plates data (FP)

The BCOM velocity was calculated from Eq. (1), where $\vec{F}(t)$ is the summed GRF, $\vec{g}$ is the gravitational acceleration and m the body mass:

$$\overrightarrow{v_{BCOM}(t)} = \int \frac{\vec{F}(t) - m\vec{g}}{m} + \vec{K} \tag{1}$$

The velocity vector of the BCOM can be projected in the natural frame attached to the force plate that defined antero-posterior (along the direction of the gait), medio-lateral (perpendicular to the direction of the gait) and vertical axes.

The integration constant $\vec{K}$ was computed for each prosthetic gait cycle from the following hypotheses(Donelan et al., 2002b):

- average medio-lateral and vertical components of the BCOM velocity over a complete gait cycle were zero
- The average antero-posterior velocity component of the BCOM velocity was calculated using the antero-posterior velocity of the centre of pressure.The latter was obtained by dividing the distance covered by the centre of pressure by the duration separating the first and the third heel-strikes on the platform, detected when the vertical force exceeded 15 N.

2.3. Comparison and validation

For each participant and each trial, three components of the instantaneous velocity of BCOM were plotted as a function of the percentage of the gait cycles. The SEG method was considered as the criterion standard.

Bland and Altman's plots were used to evaluate the agreement between the FP and MARK methods by showing the differences between the two methods as a function of the average values of the velocity from both methods.(Bland and Altman, 1986) The data's regression fit has been plotted on the graph to investigate the dependency of the bias to the velocity's nominal value. According to,(Giavarina, 2015) the average and standard deviation of the differences should be used to determine the agreement's bias and limitations.

3. Results

A total of 27 successful trials were analysed. Fig. 1 shows the BCOM velocity obtained using the three methods on a typical trial.

The Bland and Altman plots show that the difference between FP and SEG methods is less than ±0.1 m/s for each component and does not depend on 'subjects' speed for any of the three components of BCOM velocity (Fig. 2 a to c). On the contrary, the differences between MARK and SEG increased with velocity, particularly on the vertical axis (Fig. 2 d to f).

Table 1
Anthropometric data for the 8 persons with transfemoral amputation.

Subject	Gender	Age	Body mass (kg)	Height (cm)	Body Mass Index	Amputation side	Amputation cause	Amputation delay (years)
S1	M	29	73	183	21.8	Left	Traumatic	6
S2	M	54	85	181	25.9	Left	Traumatic	7
S3	M	43	72	164	26.8	Left	Traumatic	3
S4	F	49	53	165	19.5	Right	Traumatic	25
S5	M	44	47	168	16.7	Left	Traumatic	18
S6	F	26	65	165	23.9	Left	Traumatic	2.5
S7	M	32	95	180	29.3	Left	Traumatic	7
S8	M	40	95	183	28.3	Left	Traumatic	19

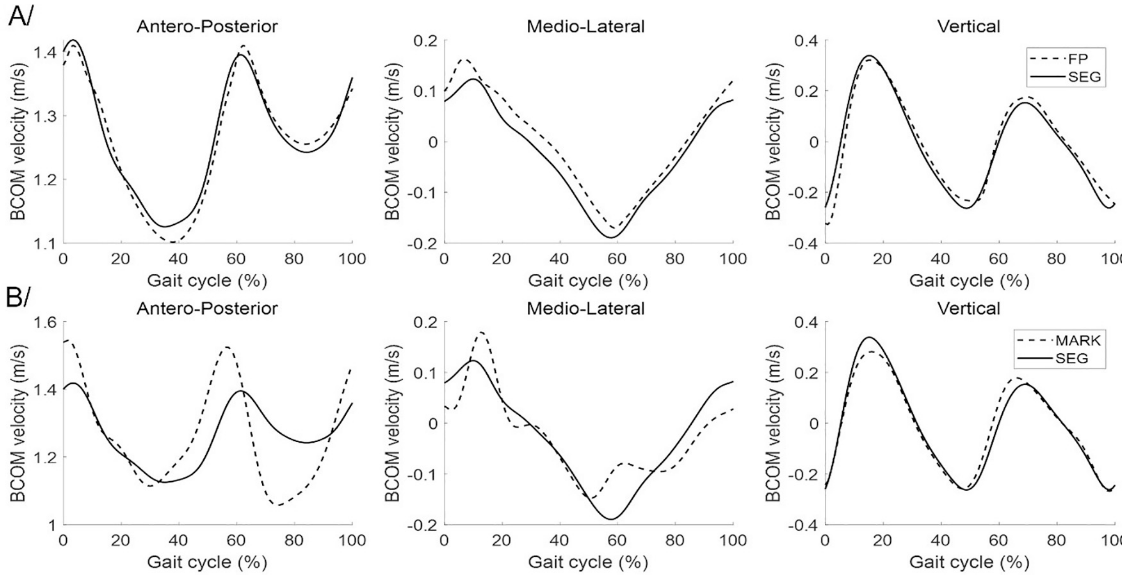

Fig. 1. BCOM velocity (m/s) for a typical participant during a single trial as calculated with the three different methods and represented according to the prosthetic cycle. First row A/: FP (force plate) vs SEG (segmental); Second row B/: MARK (markers) vs SEG.

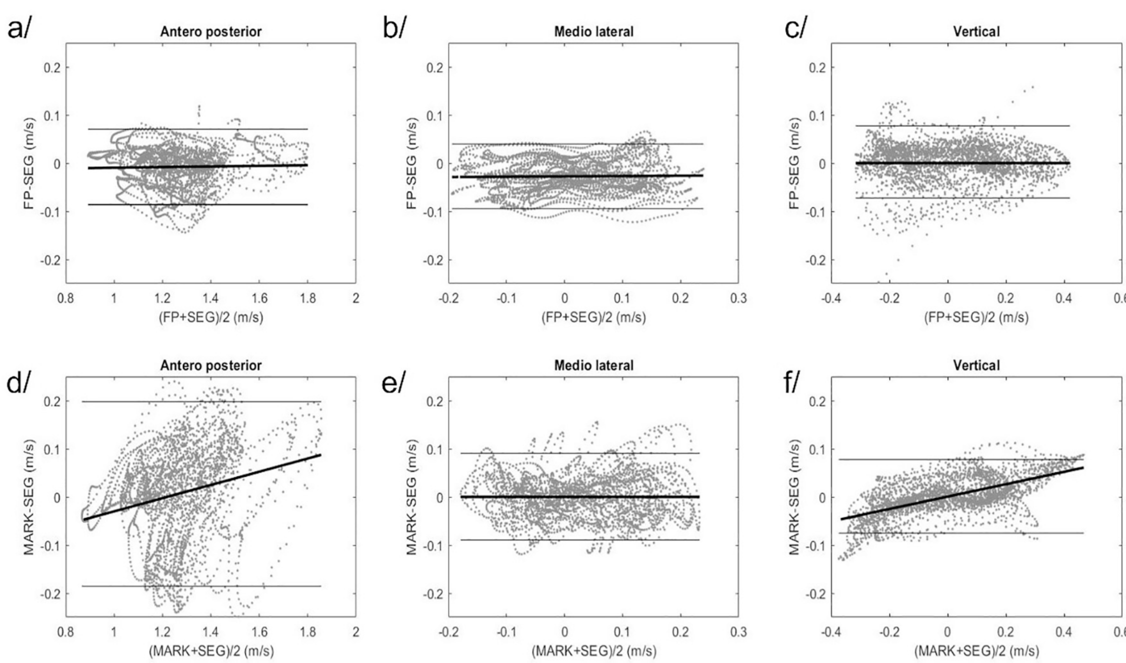

Fig. 2. Bland-Altman plots. Difference between tested (FP or MARK) and reference (SEG) instantaneous velocity at each instant and for all trials, versus the mean of the two methods. Solid bold line in the middle represents the regression line of the difference, solid thin lines are the 95% limits of agreement between methods. Subplots of the first row are FP vs SEG for the a/ anteroposterior b/ mediolateral c/ vertical components. Subplots of the second row are MARK vs SEG for the d/ anteroposterior e/ mediolateral f/ vertical components.

4. Discussion

This study's objective is to compare three methods (previously described in the literature) used to estimate the kinematics of the Body Center of Mass of people with a transfemoral amputation. Two methods (SEG and MARK) rely on motion capture from skin markers. They differentiate by the number of segments considered to estimate the position of the BCOM (only the pelvis for the MARK method and full-body segmental representation for the SEG method). The third method is a markerless force plate-based method (FP). The choice of the SEG method as the criterion standard has been motivated by previous studies on able-bodied population(Gard et al., 2004; Gutierrez-Farewik et al., 2006; Pavei et al., 2017)… Moreover, the SEG method presents the advantage of direct computation of the position of the centre of mass in the motion analysis reference frame that makes the results insensitive to the direction of the gait in the motion analysis environment.

When compared to the SEG method, the performance of the markerless FP method could be assessed. According to the prosthetic gait cycle, the pattern of the velocity evolution obtained from both methods was consistent (Fig. 1 A). MARK method shows more deviation from the criterion method (Fig. 1 B). In addition, the difference between both methods does not exceed 7.3% of the velocity range on the medio-lateral axis (1.5% and 4.8% for antero-posterior and vertical axes, respectively) (Fig. 2 a to c). Additionally, the accuracy of the FP method is not correlated with the velocity of the subject, unlike the one of the MARK method (Fig. 2 d to f). This result is consistent with previous studies showing that the approximation of BCOM by a pelvic marker was less accurate when the velocity increased.(Gard et al., 2004)

Contrary to previous studies using only two force plates,(Donelan et al., 2002b; Houdijk et al., 2009) the present protocol included three force plates, which allows computing the velocity of the BCOM over an entire gait cycle. Consequently, the hypotheses necessary to determine the integration constants could be defined without considering the symmetry between half-cycles and, therefore, between limbs. Thus, the hypothesis that the medio-lateral and vertical components average are null over a gait cycle only assumes a walk on level ground and aligned with a fixed axis of the space. This constitutes the main direction of walking and coincides with the antero-posterior axis of the force plate as defined in the method section. But, as this assumption relies only on the instruction given to the subject to walk straight, there can be a deviation from this anteroposterior axis. Although this deviation may be easily corrected with markers data, in the FP method, the subject's position relative to the force plates is unknown, and the GRF components are integrated along the plates' axes, as explained in the method section. A simple trigonometric computation can estimate the repercussion of this deviation. In the case of a 1.1 m/s velocity vector located in the horizontal plane defined by both anteroposterior and mediolateral axes, the sine of the angle between the vector and the anteroposterior axis determines the vector's projection on the mediolateral axis. In the case of a 1° angle, this projection can be estimated to 0.03 m/s. This value is in the order of magnitude of the systematic bias revealed by the Bland and Altman plot (Fig. 2 e).

No study could be found in the literature to directly compare the accuracy of the estimation of the instantaneous BCOM velocity. However, as stated in the introduction, the BCOM velocity has been used to compute clinically relevant parameters such as the power performed at the BCOM by the prosthetic limb.(Bonnet et al., 2014) The power has been shown to decrease up to 60% compared to the power performed by the sound limb of able-bodied subjects. The accuracy of the FP method is indeed sufficient to discriminate the population of people with transfemoral amputation from non-amputee persons.

If the material needed (force plates on a sufficient length of walking path) can appear as a limit of the method. In that case the acquisition of such material is far easier and less expensive thana complete motion capture system. In contrast, the fact that just the sum of ground reaction forces vectors is required is an advantage since the person may walk freely without adjusting their gait to strike the force plates individually. Even if the method is sensitive to the correct orientation of the subject regarding the force plates, a cautious protocol should limit the impact of such misorientation.

Finally, the present contribution evaluated a fully markerless assessment of instantaneous BCOM velocity from force plate for people with transfemoral amputation (FP method). The results have demonstrated that this FP method can be substituted to the SEG method with a level of uncertainty inferior to 0.1 m/s. On the contrary, the MARK method that assumes the center of mass being approximated from pelvis markers must be used cautiously considering the sensitivity of the bias to the value of the velocity. Gait assessment of amputee people is often limited by the complexity of the instrumentation and the materials involved. The simplicity of the force plate (FP) method makes it a powerful method to evaluate center of mass velocity and all related parameters in an extensive way, opening perspectives of large-scale study of the gait of people with amputation.

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