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Test–retest reliability and responsiveness of centre of pressure measurements in patients with hip osteoarthritis

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S U M M A R Y

Objective: The aim of this study was to determine a set of measures for the evaluation of balance in patients suffering from hip osteoarthritis (OA) that were both reliable and responsive to change.
Design: Three groups of subjects; Healthy, hip OA patients without surgery, and hip OA with surgery (pre and post-surgery) were included in this study. Subjects had to perform balance tests in two positions: standard and narrowed stance. CoP-based measures test–retest reliability was assessed in hip OA without surgery group, responsiveness were assessed between all groups and between pre and post-surgery.
Results: Intraclass Correlation Coefficient (ICC) values from hip OA without surgery ranged from −0.03 to 0.9 for only five parameters (CoP path length, SD velocity, mean velocity, and antero-posterior Root Mean Square (RMS_{AP})) having values over 0.7. SD velocity and RMS_{AP} showed significant differences between healthy and surgery group in standard stance whereas narrowed stance revealed most differences between all groups. RMS_{AP} showed the best responsiveness (Standardized Response Mean ~0.5) between pre vs post-surgery in both conditions. RMS_{AP} was also capable of discriminating between hip OA with surgery vs without surgery groups with good sensitivity and specificity.
Conclusions: Our results showed there to be reliability and responsiveness of five postural parameters in hip OA patients in two conditions of standing balance. More parameters were significantly different in narrowed stance whereas sensitivity was better in standard stance. SD velocity and RMS_{AP} discriminate between degrees of OA severity and highlight potential balance deficits even after arthroplasty. Selected parameters during standing balance could be assessed to complete the set of quantitative measures to quantify hip OA patient deficiencies.

Introduction

Osteoarthritis (OA) of the hip is a common musculoskeletal disease affecting many individuals causing pain and a decrease in physical function, thus limiting an individual's participation in society and reducing their Quality of life (QoL)[1,2].

Measurement of functional impairment is a critical component of research and clinical practice because it drives the choice of therapy prescribed[3–5]. Measurement of physical function is complex however, as it is a multi-dimensional construct[6–8]. A range of both self-reported and performance-based measures should be used to assess physical function[5]. Performance-based measures are defined as assessor-observed measures of tasks classified as "activities" using the ICF model[8] and are usually assessed using quantifiable measurements. Increasing evidence suggests that

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performance-based measures capture a different construct of function and are more likely to fully characterize a change in body function than self-reported measures alone[9,10].

The integrity of balance function is critically linked to falls in older people[11]. Balance control allow one to move or to efficiently stabilize our center of mass during daily activities, such as lower body dressing, ambulating, reaching to grasp and manipulate objects, or even climbing stairs; all essential activities that become increasingly challenged with aging[11,12]. Indeed, falls occur mainly during activities of dynamic equilibrium[13]. Nonetheless, postural instability during quiet stance should not be ignored since it constitutes an underlying risk factor for falls[14–17]. Within this context, two main points must be considered. First, the hip joint is a critical source of somatosensory inputs[18] contributing to both static and dynamic balance control. Indeed, the hip joint plays an important role in maintaining balance[19], particularly in the frontal plane[18,20,21]. Other evidences of the hip acting as an important stabilizing joint has arisen through the study of the deleterious effects of fatiguing the hip muscles upon postural control[22,23]. Second, hip OA is itself considered a risk factor for falls in elderly adults[24–26]. Taken together, these considerations warrant a detailed assessment of standing balance in the management of hip OA.

The variables most commonly used to describe postural stability (e.g., path length, area, mean velocity, *etc.*) are derived from the spatiotemporal patterns of the center of pressure (CoP), the barycenter of all forces acting downwards on the body[27,28]. Conclusions about stability from CoP displacements are possible as they are directly proportional to ankle torque[29], which is regulated via descending motor commands, mechanical properties of the surrounding ankle musculature[30,31] and the cutaneous sensory input[32,33]. Importantly, recent evidence has suggested that the excursion of the CoP within the base of support (BoS) reflects an exploratory mechanism that enables humans to acquire and use sensory information, indicating that postural sway may actually be important for balance control[34,35].

Thus, the manner in which hip OA modifies the characteristics of sway is essential to understand, as it has implications not only for these patients' ability to conserve their balance, but also in their ability to use excursions of the CoP to improve balance control, post-surgery. However, the precise selection of sway measures for clinical use should be motivated primarily by their reliability and responsiveness[36]. The objective of this study was therefore to determine using a stepwise method, a set of measures that were reliable and responsive to change, for the evaluation of postural steadiness in patients suffering from hip OA.

Methods

Study design and settings

This study incorporated three stages; the first was to identify a set of reliable parameters from those recommended in the literature. The second was to select only those parameters in terms of their responsiveness to differences in the patient groups and the third was to quantify the construct and convergent validity. Thus, this study assessed postural steadiness of hip OA patients of different severities (indication of surgery or not) compared to healthy controls. All participants were recruited by an experienced rheumatologist (PO, JFM). The inclusion period extended from January 2008 to December 2013. Protocols were approved by the local ethics committee (CPP Est I, Dijon, France) and conformed to the Declaration of Helsinki. All patients signed an informed voluntary consent form prior to their participation. Trials were registered on Clinicaltrials.gov (NCT02042586 and NCT01907503).

Participants

The CONSORT diagram (Supplementary Materials) describes the recruitment process and the sample sizes for the participants in this study. Three groups of participants, aged 40–80 years, were recruited for this study. (1)HEA: healthy persons without symptomatic musculoskeletal disease; (2)COX: patients with unilateral symptomatic hip OA, defined using the American College of Rheumatology criteria[37]. Other inclusion criteria were Kellgren and Lawrence stages (II–IV)[38], and no indications of surgery. (3)SURG: patients with unilateral symptomatic hip OA with indication of total joint replacement. Patients in this group were evaluated 15 days before ($SURG_{M0}$), and 6 months after surgery ($SURG_{M6}$). The surgical approach was chosen by an experienced surgeon between antero-lateral-type (Rottinger) or posterior approaches (Moore), depending on each patient's hip OA feature. Indication of surgery was defined as severe hip pain and/or functional limitation despite conservative treatments (including analgesics, NSAIDs) and rehabilitation, according to the surgeon's opinion.

Exclusion criteria were: secondary hip OA, inflammatory hip OA, significant painful ankle, knee or foot disorders, chronic back pain, Parkinson's disease, motoneuronal disorders, non-stabilized diabetes mellitus, cardiac or respiratory insufficiency and an inability to understand the procedures.

Functional self-reported instrument

The Hip disability and Osteoarthritis Outcome Score (HOOS)[39,40], a well-validated, self-administered questionnaire developed and validated as an extension of the Western Ontario and McMaster Universities Arthritis Index (WOMAC)[41] for hip OA patients, regardless of the degree of disease severity was used. The HOOS includes five domains, i.e., pain, other symptoms, activities of daily living (ADL), sport and recreation function (SP), and hip related QoL, Standardized answer options are given (five Likert boxes) and each question gets a score from 0 to 4. A normalized score (from 0-worst) to (100-best) for each HOOS subscale was calculated for both OA groups.

Data collection

Patients were required to stand as still as possible on a force platform for trials lasting 54 s (SOFPEL guidelines[42]), in two different BoS configurations. A first, standard position corresponded to a mediolateral distance between the feet that was the same as shoulder width (standard BoS). The distances were controlled by a 3D optoelectronic system (Vicon, Oxford, UK), by real-time measurements of the inter-acromial and inter-external malleolus distances with reflective markers positioned on such landmarks. A second position required participants to stand with their feet together (narrowed BoS). An experimenter stood beside the participant at all times for safety. Standardized oral instructions to "stand quietly, with the arms by the sides of the body and to focus on a target placed on the wall at eye level" were given to the participants before each trial.

Data analysis

Force-platform data were recorded using an AMTI platform (AMTi®, USA). In order to comply with the SOFPEL recommendations for signal processing[42] all signals were first recorded at 1000 Hz then downsampled to 40 Hz. We then removed 1.2 s from the beginning and end of each trial to keep 51.6 s of data. Signals were filtered with a low-pass zero-phase shift Butterworth filter with a 10 Hz cut-off frequency. Centre of pressure position was expressed using the force-platform reference.

We considered the nineteen following quantitative CoP parameters for the analyses, according to the recommendations of[27,28] and computed using Matlab® (The Mathworks, Natick, USA):

- Length indicators: path length (L, mm), mean velocity (Vmean, $mm.s^{-1}$), anteroposterior and mediolateral amplitudes (AP/ML amplitude, mm), maximal velocity of the CoP (Max Velocity, $mm.s^{-1}$), standard deviation of the velocity (SD velocity, $mm.s^{-1}$), assymetry of the CoP position (BoS asymmetry, % of the inter-external-malleolus distance, 0 is the central position).
- Surface indicators: area of the ellipse encompassing 95% of CoP samples (Ellipse area, mm^2) and the ratio with the path length (L/E ratio). Root mean square of anteroposterior and mediolateral oscillations were calculated as follows:

$$RMS = \sqrt{\frac{1}{N}\sum_{n=1}^{N} X_n^2} \quad (1)$$

With X_n being the nth point of the displacements of the centre of pressure axis and N, the number of samples in the analysis.

- Oscillatory indicators: Mean (MNF) and median (MDF) of the anteroposterior and mediolateral frequencies of oscillations (MNFAP/ML; MDFAP/ML, Hz) calculated using the following formula:

$$MNF = \frac{\sum_{i=1}^{N} SPF_i \times fi}{\sum_{i=1}^{N} fi} \quad (2)$$

$$MDF = f_i \; as \int_1^{f_i} SPF(i)di = \frac{\int_1^{\infty} SPF(i)di}{2} \quad (3)$$

with SPF_i, and f_i representing the ith value of the power spectrum and the respective frequencies of the waveforms of the displacements of the CoP along the axes, and N being the number of samples in the analysis.

- Fractal indicators[43,44]: Detrended Fluctuation Analysis exponent (DFA) Hurst rescaled range analysis exponent ($H_{R/S}$) of the anteroposterior and mediolateral oscillations.

Statistical analysis

We aimed to identify a set of variables that showed both good reliability and good responsiveness (for details see[45]). We then proceeded in the following manner:

The first stage identified the reliable parameters among those computed: The reliability domain contains various measures for continuous data, the test–retest reliability, the measurement error and the minimal detectable change (MDC).

- Test–retest reliability (COX group only)

Two standing balance analyses were carried out at the same time of the day at a maximum of 7 days interval by a single experienced investigator (DL) who was blinded to all previous measurements. The 2-way Intraclass Correlation Coefficient ($ICC_{(2,1)}$) was calculated to assess relative reliability using a two-way random effect with a single measure of absolute agreement. An ICC greater than 0.7 was considered good and an ICC over 0.9, excellent[46].

- Standard error of measurement (SEM)

The SEM was chosen to test absolute reliability[46] and to represent the absolute error of a measurement. The following formula was used:

$$SEM = \delta^2 \sqrt{1 - ICC} \quad (4)$$

where δ^2 = standard deviation of the measurement. SEM was also expressed relative to the mean of the two measures (%). A SEM lower than 15% was considered as good in line with previous studies[47,48].

- MDC

This parameter addresses the problem of deciding if the result is significant or not. It defines the absolute or relative change that is not due to the variation in the measurement. It was computed in absolute or relative terms using the follow formulae, respectively:

$$MDC = SEM \times 1.96 \times \sqrt{2} \quad (5)$$

$$95\% \; MDC = MDC * \frac{100}{session1 \; mean \; value} \quad (6)$$

- Bland and Altman representation

In order to evaluate the distribution of the difference of the means between sessions, Bland and Altman plots were obtained by plotting the difference in COP measures between the two test sessions against the mean results[49]. The Bland and Altman representations make it possible to describe the percentage of subjects and their distribution within the 95% limits of agreement throughout the range of each COP measure. The smallest detectable difference (SDD), which corresponds to the limits of agreement (mean change ± 1.96 SD) represents the smallest change that can be distinguished from the measurement error for each parameter.

The second step tested the responsiveness of the parameters found to be reliable and with low SEM (<15%) resulting from step one. The responsiveness domain reflects the sensitivity to change and is frequently inferred using statistical tests and quantified using the Standard Response Mean (SRM).

- Inter-group differences

A multivariate analysis of variance (MANOVA) was used to detect differences between groups, sessions and tasks (i.e., standard BoS × narrowed BoS × HEA × COX × $SURG_{M0}$ × $SURG_{M6}$) for each of the posturographic parameters. When a significant effect was found, a LSD *post-hoc* was carried out to identify potential differences.

- Standardized Response Mean

SRM is based on the distribution of the difference between two measurements. SRM was then only computed for patients in the SURG groups between M0 and M6. SRM was computed by dividing the mean change score of the values of $SURG_{M0}$ and $SURG_{M6}$ by the standard deviation of the change score. (SRM 0.20 indicating a "trivial" change, SRM between 0.20 and 0.50 "small," SRM of 0.50–0.80 a moderate, and SRM 0.80 a large change)[50].

∘ Receiver Operation Characteristic (ROC)

ROC curves were computed to assess the sensitivity and specificity the reliable parameters. The Youden index (Yi) was used to find the optimal threshold values for each variable entered in the analysis[51].

The third step partially assessed the validity domain, which refers to the degree to which an instrument measures the constructs that it is supposed to measure.

∘ Convergent validity

The convergent validity estimates the consistency of measurement. As all variables came from derived measures of CoP, we tested the hypothesis that some parameters were closely linked and evolve together (i.e., measure the same construct). To test this hypothesis we used Pearson correlation coefficient and Kendall coefficient of concordance.

∘ Criterion validity

Parameters found to be reliable and sensitive to change were tested in order to reveal the degrees to which the measurements were an adequate reflection of the HOOS scores which is considered gold standard for the measurement of function in patients with Hip OA.

Mean and 95% confidence intervals (CIs) were computed for each variable and each participant. Statistical analyses were conducted using the Statistica (Statsoft, Tulsa, USA) v10.0. A significance level of $P < 0.05$ was adopted. Strength of Pearson correlation was based on Munro's correlation descriptors (very low = 0.15–0.24, low = 0.25–0.49, moderate = 0.50–0.69, high = 0.70–0.89, and very high = 0.90–1.00)[52].

Results

Participants

Twenty-six healthy participants, thirty-nine COX patients and seventy-eight $SURG_{M0\&M6}$ patients were included in this study. Enrollment and allocation of all participants are described in the CONSORT flow diagram in Supplementary Materials 1. Participant characteristics are shown in Table I. HOOS score were significantly improved between $SURG_{M0}$ and $SURG_{M6}$. HOOS score for $SURG_{M0}$ were also significantly lower than those of COX group. This trend was opposite for $SURG_{M6}$ (see Table I).

Reliability

$ICC_{(2,1)}$ values of CoP parameters ranged from −0.03 to 0.9 with only five out of nineteen having ICC values greater than 0.7, which can be considered as being good[46] (Table II). Center of pressure (CoP) path length, mean velocity, max velocity, the SD of CoP velocity and RMS_{AP} all displayed high reliability except for CoP max velocity, which displayed low ICC values in the narrowed BoS condition. SEM values can be found in Table III. These values were low for Max CoP velocity in both conditions (standard and narrowed BoS). However, path length, mean and SD of CoP velocity and RMS_{AP} all exhibited good SEM values in one or both conditions and have been conserved for further analysis. MDC_{95} was high for these parameters except for RMS_{AP} in both conditions. Bland–Altman plots are presented in Fig. 1 and show clearly that no evident relationship existed in the differences between the two standing balance analyses and the mean (means of the two analyses) of the CoP measures.

Table I
Characteristics of the participants. (HEA: Healthy Group, COX: Hip Osteoarthritis group without surgery; SURG: Hip Osteoarthritis group surgery; M0: 15 days before surgery; M6: 6 months after surgery).*significant difference ($P < 0.05$) vs COX group. $: Significant difference ($P < 0.05$) between M0 and M6

	HEA	COX	SURG	
			M0	M6
Sex (H/F)	12/14	18/20	42/36	
Height (cm)	163.7 (8.1)	166.9 (8.6)	165.4 (8.6)	
Age (years)	68.2 (8.1)	60.7 (8.3)	65.9 (9.1)	
Weight (kg)	66.9 (14.5)	74.5 (12.3)	78.9 (17.7)	
Body mass index	24.8 (4)	26.6 (3)	28.7 (5.4)	
Lequesne scale		7.57 (2.57)		
Kellgren & Lawrence grade				
II		19	13	
III		18	37	
IV		1	28	
HOOS symptoms		61.1 (16.2)	41.7 (19.6)*	84 (14.3)$*
HOOS pain		57.5 (15.4)	40.1 (17.7)*	87.4 (13.3)$*
HOOS function		59.1 (18.9)	38 (17.2)*	83.1 (15)$*
HOOS activities		44 (19.7)	23 (19.5)*	73.1 (22.9)$*
HOOS QoL		47.6 (18.9)	25.8 (21.9)*	82 (19.1)$*

Responsiveness

Significant differences existed for a number of variables between standard BoS (normal stance width) and narrowed BoS (narrow stance width) for all participants in terms of responsiveness. In the standard BoS configuration, the RMS_{AP} and SD of CoP velocity both showed significant differences between $SURG_{M0\&M6}$ and HEA groups ($P < 0.05$) (see Table IV). Moreover, in this condition, RMS_{AP} was significantly lower in the SURG group than in the COX group by some 18% ($P < 0.05$).

In the narrowed BoS condition, all variables measured showed that the HEA group and $SURG_{M0}$ group were significantly different ($P < 0.05$, see Table IV). However, only the RMS_{AP} measure provided a significant difference between the HEA group and the COX group (9% lower in the latter group). In the narrowed BoS condition, Path length, Mean CoP Velocity, and the SD of CoP Velocity were significantly higher in the $SURG_{M0}$ group than in the COX group (respectively 20%, 20.8% and 24% higher). In the same condition, Path length, Mean CoP Velocity, and RMS_{AP} were sufficiently sensitive to detect the changes due to surgery in between the $SURG_{M0}$ and $SURG_{M6}$ group (respectively an increase of 16%, 15% and 5%).

SRM was close to 0.5 for RMS_{AP} in both conditions, whereas SRM was low for the others parameters in both conditions (SRM<0.3; Table IV). Only RMS_{AP} in standard BoS showed a good profile when plotting as a ROC curves: this variable was particularly effective at categorizing COX group and $SURG_{M0}$ group. Figure 2 shows the ROC curves for RMS_{AP} in standard BoS and narrowed BoS for discriminating COX group and $SURG_{M0}$ group. In standard BoS an RMS_{AP} cut-off value of 121.12 was found by calculating Yi (best Yi = 0.557). This index corresponds to a sensitivity of 0.747 and a specificity of 0.810.

Convergent and criterion validity

Pearson correlation and significant Kendall coefficients revealed that Path length, Vmoy and SDvelocity were all highly correlated in normal and narrowed stance (Pearson $r > 0.80$, $P < 0.001$; Kendall $r = 0.98$ and $r = 0.99$ respectively). Kendall coefficient values decreased when RMS_{AP} was added in normal and narrowed stance

Table II
CoP based-measures of the session 1 and session 2 for the hip OA group without surgery only. Mean and SD of each session were calculated as well as the 2-way $ICC_{(2,1)}$ and its 95% CI. Good values (>0.7) are represented in Bold

CoP based-measure	Standard BoS			Narrowed BoS		
	Session 1 mean (95% CI)	Session 2 mean (95% CI)	$ICC_{(2,1)}$ (95% CI)	Session 1 mean (95% CI)	Session 2 mean (95% CI)	$ICC_{(2,1)}$ (95% CI)
Path length (mm)	543 (186–900)	544 (260–828)	**0.85 (0.64–0.95)**	999 (476–1522)	1032 (517–1547)	**0.75 (0.41–0.91)**
Ellipse area (mm^2)	117 (−18–252)	154 (−73–381)	0.52 (0.08–0.8)	360 (1–719)	423 (119–727)	0.26 (−0.22–0.65)
Path length/Ellipse ratio	6 (−0.5–12.5)	4.6 (0.3–8.9)	−0.03 (−0.5–0.46)	5.6 (−15–26)	2.7 (1–4)	0.3 (−0.15–0.67)
Max velocity (mm.s^{-1})	61.4 (13.6–109.2)	56.3 (6.7–105.9)	**0.76 (0.44–0.91)**	88 (23.5–152.5)	85.4 (39.9–130.9)	0.47 (−0.02–0.77)
Mean velocity (mm.s^{-1})	10.5 (3.4–17.6)	10.6 (−10.2–31.4)	**0.85 (0.64–0.95)**	19.5 (9.3–29.7)	20.2 (10.2–30.2)	**0.75 (0.41–0.91)**
Std velocity (mm.s^{-1})	7.68 (2.09–13.27)	7.5 (2.25–12.75)	**0.72 (0.36–0.89)**	12.53 (5.89–19.17)	12.49 (6.41–18.57)	**0.82 (0.57–0.93)**
BoS assymetry	−0.03 (−0.17–0.11)	−0.02 (−0.2–0.16)	0.44 (−0.07–0.77)	−0.12 (−0.3–0.06)	−0.12 (−0.39–0.15)	0.54 (0.07–0.81)
AP amplitude (mm)	29.61 (9.05–50.17)	29.18 (4.33–54.03)	0.3 (−0.24–0.69)	31.82 (17.81–45.83)	32.55 (17.4–47.7)	0.56 (0.09–0.82)
AP RMS	112.38 (85.49–139.27)	108.74 (82.5–134.98)	**0.9 (0.75–0.97)**	117.33 (85.83–148.83)	117.78 (90.54–145.02)	**0.8 (0.51–0.93)**
AP MNF (Hz)	1.85 (0.81–2.89)	2.09 (0.99–3.19)	0.44 (−0.04–0.76)	1.8 (0.72–2.88)	1.42 (0.6–2.24)	0.18 (−0.29–0.6)
AP MDF (Hz)	0.67 (0.26–1.08)	0.6 (0.23–0.97)	−0.03 (−0.48–0.45)	0.76 (−0.42–1.94)	0.57 (0.35–0.79)	0.5 (0.06–0.79)
DFA exponent AP	1.37 (1.21–1.53)	1.32 (1.16–1.48)	0.07 (−0.26–0.42)	1.26 (1.08–1.44)	1.29 (1.13–1.45)	0.55 (0.20–078)
$H_{r/s}$ exponent AP	0.88 (0.78–0.98)	0.86 (0.76–0.96)	0.08 (−0.36–0.49)	0.85 (0.73–0.97)	0.88 (0.76–1)	0.6 (0.22–0.82)
ML amplitude (mm)	12.21 (−3.61–28.03)	12.07 (4.86–19.28)	0.14 (−0.39–0.59)	31.43 (10.5–52.36)	33.32 (18.23–48.41)	0.2 (−0.35–0.63)
ML RMS	12.48 (−5.3–30.26)	13.32 (−19.96–46.6)	0.36 (−0.16–0.72)	10.74 (1.35–20.13)	12.42 (−13.88–38.72)	0.4 (−0.13–0.74)
ML MNF (Hz)	1.59 (0.45–2.73)	1.57 (0.69–2.45)	−0.4 (−0.8–0.15)	1.79 (0.85–2.73)	1.85 (0.69–3.01)	0.14 (−0.41–0.59)
ML MDF (Hz)	0.43 (0.18–0.68)	0.46 (0.22–0.7)	0.47 (−0.03–0.78)	0.57 (0.35–0.79)	0.55 (0.28–0.82)	0.68 (0.31–0.87)
DFA exponent ML	1.21 (0.86–1.56)	1.23 (0.99–1.47)	0.13 (−0.31–0.51)	1.23 (1.05–1.41)	1.21 (1.07–1.35)	−0.02 (−0.44–0.39)
$H_{r/s}$ exponent ML	0.83 (0.71–0.95)	0.87 (0.77–0.97)	0.06 (−0.25–0.41)	0.85 (0.73–0.97)	0.84 (0.74–0.94)	0.41 (0–0.71)

(Kendall $r = 0.55$ and $r = 0.63$ respectively) and RMS_{AP} was not linked to these other variables whatever the condition (Pearson $r < 0.2$, $P > 0.05$). Correlations were found between RMS_{AP} and the HOOS scores (Supplementary Materials 2) only for the normal stance condition ($r \leq 0.4$, $P < 0.05$ and $r < 0.15$, $P > 0.05$ respectively).

Discussion

The objective of this study was to propose a set of kinetic parameters that are reliable and responsive to change in order to assess sway in hip OA patients. Overall, our results have shown that COP-based measures have diverse levels of reliability whatever the postural condition. Among these parameters, mean velocity, SD of velocity, CoP path length and RMS_{AP} were the most reliable and responsive to change. The narrowed stance condition revealed more differences between groups. Whereas mean velocity, SD of velocity, CoP path length measure the same construct, RMS_{AP} seems to measure a different one. This result highlights the importance of combining at least two variables (i.e., RMS_{AP} and SD of velocity) in different conditions in order to detect postural deficiencies.

This work does have several potential limitations. First, we did not evaluate the reliability of CoP parameters in SURG group; this can potentially limit the generalizability of our results in hip OA patients. Therefore, the reliability of these postural parameters in pre operative patients should be assessed in further studies. Second, we did not evaluate the somatosensory aspects of posture (eyes closed). This is because our main goal was to record potential hip neuromuscular deficits in hip OA patients, and reducing BoS size sufficed to reveal differences. Third, we tested patients at mid-term (6 months) post-surgery, so it was unsurprising to discover persistent deficits. Further studies are needed to evaluate postural balance adaptation at long-term (>1 year) in OA patients. Finally, the evaluation proposed in this study could be expensive and time consuming compared to other clinical tests. Therefore, further

Table III
Raw SEM, relative SEM (SEM(%)) and MDC of the CoP based-measures computed from ICC of hip OA in the without surgery group

CoP based-measure	Standard BoS				Narrowed BoS			
	SEM	SEM (%)	95% MDC	95% MDC (%)	SEM	SEM (%)	95% MDC	95% MDC (%)
Path length (mm)	**74.2**	**13.65**	**205.67**	**37.88**	**94.79**	**9.33**	**262.75**	**26.3**
Ellipse area (mm^2)	63.2	46.64	175.17	149.72	100.04	25.55	277.29	77.03
Path length/Ellipse ratio	1.85	34.91	5.12	85.33	5.13	123.61	14.21	253.75
Max velocity (mm.s^{-1})	15.02	25.52	41.62	67.79	12.6	14.53	34.93	39.69
Mean velocity (mm.s^{-1})	**1.45**	**13.68**	**4.02**	**38.29**	**1.85**	**9.32**	**5.13**	**26.31**
Std velocity (mm.s^{-1})	**1.3**	**16.9**	**3.61**	**47.01**	**1.23**	**9.8**	**3.43**	**27.37**
BoS assymetry	0.05	10	0.13	−433.33	0.07	58.33	0.2	−166.67
AP amplitude (mm)	6.56	22.32	18.17	61.36	4.84	15.04	13.41	42.14
AP RMS	**5.61**	**5.07**	**15.55**	**13.84**	**4.38**	**3.73**	**12.13**	**10.34**
AP MNF (Hz)	0.37	18.78	1.03	55.68	0.31	19.25	0.87	48.33
AP MDF (Hz)	0.12	18.9	0.33	49.25	0.29	43.61	0.81	106.58
DFA exponent AP	0.05	4	0.15	10.95	0.05	3.71	0.14	11.11
$H_{r/s}$ exponent AP	0.04	4.65	0.1	11.36	0.03	3.44	0.1	11.76
ML amplitude (mm)	4.19	34.51	11.62	95.17	6.3	19.46	17.46	55.55
ML RMS	8.51	65.97	23.57	188.86	6.41	55.35	17.77	165.46
ML MNF (Hz)	0.35	22.15	0.97	61.01	0.35	19.23	0.96	53.63
ML MDF (Hz)	0.06	13.48	0.18	41.86	0.08	14.29	0.21	36.84
DFA exponent ML	0.1	8.2	0.28	23.14	0.06	4.92	0.16	13.01
$H_{r/s}$ exponent ML	0.04	4.73	0.11	13.25	0.03	3.53	0.1	11.76

Bold indicate values kept for further analysis (SEM <15% for Standard or Narrowed conditions).

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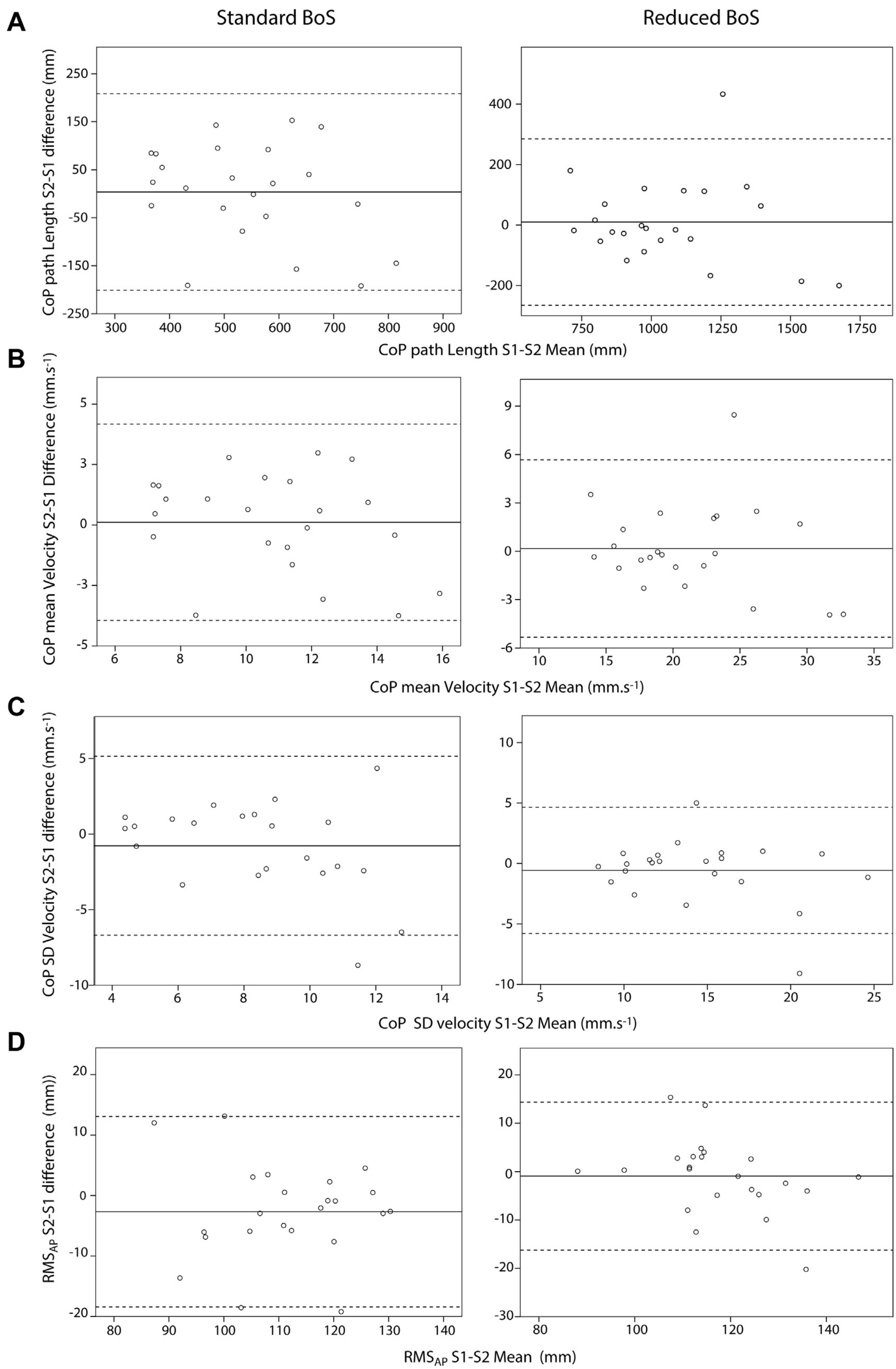

Fig. 1. Bland–Altman plots showing differences in CoP path length (A), CoP mean velocity (B), the standard deviation of CoP velocity (C) and CoP A/P root mean square values (D) from the beginning (S1) to the end (S2) of recording.

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Table IV
Responsiveness of the reliable CoP based-measures. *significant difference ($P < 0.05$) vs HEA; $significant difference ($P < 0.05$) COX and SURG at M0; µsignificant difference ($P < 0.05$) between SURG at M0 and M6

CoP based-measure	Standard BoS					Narrowed BoS				
	HEA mean (95% CI)	COX mean (95% CI)	SURG mean (95% CI)		SRM (M0 vs M6)	HEA mean (95% CI)	COX mean (95% CI)	SURG mean (95% CI)		SRM (M0 vs M6)
			M0	M6				M0	M6	
Path length (mm)	492 (240–745)	623 (31–1214)	700 (125–1275)	668 (156–1180)	0.2	1051 (406–1696)	1082 (291–1872)	1297$^{\$*}$ (216–2377)	1503^{µ} (−110–3115)	0.28
Mean velocity ($mm.s^{-1}$)	9.6 (4.7–14.6)	12.2 (0.6–23.7)	13.8 (2.5–25.2)	13.3 (1.1–25.5)	0.15	20.5 (7.9–33.1)	21.1 (5.7–36.6)	25.5$^{\$*}$ (4.4–46.6)	29.4^{µ} (−2.1–60.9)	0.24
SD of velocity ($mm.s^{-1}$)	6.2 (2.5–9.9)	8.3 (−0.7–17.3)	10.7* (−3.4–24.8)	9.1 (−0.6–18.9)	0.25	12.7 (5.1–20.3)	13.2 (4–22.5)	16.4$^{\$*}$ (2.3–30.5)	18.6 (−2.3–39.5)	0.12
AP RMS	134.6 (74.6–194.6)	135 (106.6–163.4)	111$^{\$*}$ (77–145.9)	116 (84.3–148.4)	0.51	132 (106.5–158.5)	121* (93.2–149.3)	117* (85.6–149.3)	123^{µ} (90.4–155.6)	0.47

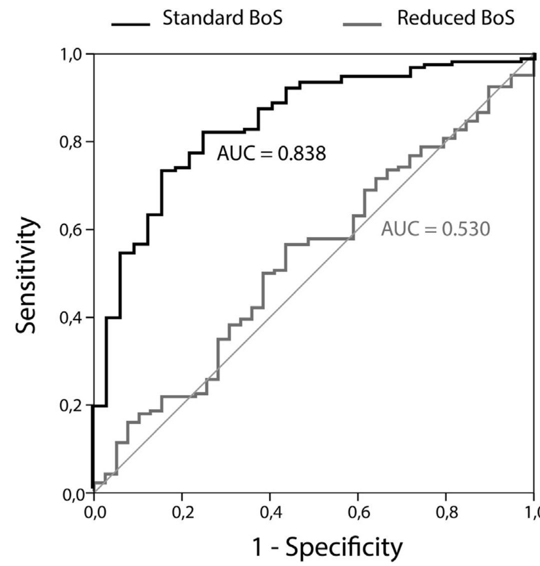

Fig. 2. ROC curves for standard BoS and Narrowed BoS conditions.

studies should explore the entire validity (predictive validity, criterion validity construct validity, *etc.*) between the set of outcomes documented here and more clinical tests such as the timed up and go test[51,52].

Only five of the parameters tested were sufficiently reliable to perform the sensitivity procedures in this study. This low number of reliable variables was quite unexpected as several other posturographic parameters have demonstrated good reproducibility both in knee OA patients[48,53], SCI patients[45] and healthy subjects[28,31,43]. These studies however, have provided conflicting evidence of the best postural parameters to adopt when evaluating changes in postural control following joint disorders. One may hypothesize that the hip is a critical joint (as well as the ankle) to control balance contrary to the knee that could be assimilated to a strain system. Thus, an impairment of the hip might impact standing to a greater extent (i.e., less reliable) than an impairment of the knee does. We may also hypothesize that patients with severe hip OA try to maintain a position that reduces the constraints and pain on the femoral head. It is interesting to note that 6 months after arthroplasty, the $SURG_{M6}$ group showed a more flexible postural control, evidenced through an increase of RMS_{AP}, but not better in terms of stability, as demonstrated by the increase of SD velocity and path length (path length > MDC between $SURG_{M0}$ and $SURG_{M6}$). With the decrease in hip pain and stiffness, patients might explore their space but with a narrowed level of neuromuscular control and their modified somatosensory inputs are unable to effectively manage their pelvis motion, thus leading to a greater potential risk of falling. Interestingly, a reduction in neuromuscular control through narrowed proprioception has previously been highlighted in patients who received knee surgery[54].

Our ROC analyses showed substantial sensitivity of the RMS_{AP} parameter as a function of the degree of disease severity (COX vs $SURG_{M0}$) in the standard BoS configuration. Moreover, a potential reduction in RMS_{AP} was found for the $SURG_{M0}$ group that can be interpreted as a tendency towards postural stiffness as previously described for Parkinson patients[55]. Therefore, the increase in RMS_{AP} may reflect an adaptation of patients with hip OA in light of their greater risk of falling[56]. From a signal-processing viewpoint, the RMS_{AP} parameter corresponds to the square integral of the position of the subject in the antero-posterior axis (i.e., Area Under the Curve). Simply put, in this condition, the RMS_{AP} corresponds to the

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quantity of movement produced by the subject along the antero-posterior axis. However, the calculating methods used induce bias in the interpretation of this parameter. It is not possible to distinguish if the patient had spikes along their curves close to the force platform reference or were far from the reference with stable curves. Thus, to clearly evaluate the balance function, RMS_{AP} should be interpreted with other parameters indicating the variation of CoP movement such SD velocity. If RMS_{AP} and SD velocity both move with the same sign, an increase could indicate a potential increase in instability, whereas a decrease would signify a postural stiffness. Equally, if RMS_{AP} and SD velocity move in opposition, with low SD velocity and high RMS_{AP}, increased stability could be argued for. Finally, with low RMS_{AP} and high SD velocity, which may potentially be the worst-case scenario, potentially greater instability would ensue.

The decision process used by the experienced rheumatologist to propose, or not, a surgery intervention, has traditionally been based on a multidimensional approach. Nowadays, the decision is mainly based on pain level, X-ray grades, a decrease in QoL and functional scores, even if it may still be influenced by a 'surgeon culture'[57]. We propose therefore that our set of postural parameters could be useful in evaluating balance function following surgery as well as providing a more subjective evaluation for the surgeon or patient[58]. However, most of the parameters showed an important CI (as revealed by the MDC), and should be interpreted with caution. Thus, it is particularly important to define cut-off levels for the most relevant parameters: RMS_{AP} cut-off value was determined by ROC analysis with good discriminant capacity between non severe vs severe hip OA, which needs to be confirmed in further studies. Moreover, RMS_{AP} during the standard BoS configuration demonstrated a significant relationship with HOOS scores (see Supplementary Materials 2), which directly supports the external validity of this outcome measure. Despite the link between postural steadiness and functional impairment in daily living[59], it seems that these posturographic parameters do not measure the same dimension of function and are complementary to the HOOS.

In conclusion, this study has demonstrated the reliability and responsiveness of only five postural parameters in hip OA patients, however we suggest that further studies are required to confirm these results. These parameters allowed us to discriminate between degrees of OA severity and highlight potential balance deficits even after arthroplasty. This result is of particular relevance because the risk of falls in patients after surgery is a significant problem, and tests such as these might help selecting patients that need more specific rehabilitation strategies. Standing balance assessments for hip OA patients are of particular interest, especially those that are quick and clinically relevant with moderate cost. They could be offered to complement the proposed set of quantitative measures in order to assess patient deficiencies.

Contributorship statement

Davy Laroche: Conception and design, Analysis and interpretation of the data, Drafting of the article, Final approval of the article, Provision of study materials or patients, Statistical expertise, Administrative, technical, or logistic support, Collection and assembly of data.

Alexandre Kubicki: Conception and design, Analysis and interpretation of the data, Drafting of the article, Final approval of the article, Critical revision of the article for important intellectual content.

Paul J Stapley: Analysis and interpretation of the data, Drafting of the article, Final approval of the article, Critical revision of the article for important intellectual content.

Vincent Gremeaux: Analysis and interpretation of the data, Drafting of the article, Final approval of the article, Critical revision of the article for important intellectual content.

Katia Mazalovic: Conception and design, Provision of study materials or patients, Administrative, technical, or logistic support.

Jean-Francis Maillefert: Statistical expertise, Critical revision of the article for important intellectual content, Conception and design.

Paul Ornetti: Conception and design, Analysis and interpretation of the data, Drafting of the article, Critical revision of the article for important intellectual content, Final approval of the article, Provision of study materials or patients, Statistical expertise, Collection and assembly of data.

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Competing interest

The authors have no conflict of interest to declare.

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Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.joca.2015.03.029.

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