Clinical Biomechanics 32 (2016) 171–179

Contents lists available at ScienceDirect

Clinical Biomechanics

journal homepage: www.elsevier.com/locate/clinbiomech

Assessment of physical function following total hip arthroplasty: Inertial sensor based gait analysis is supplementary to patient-reported outcome measures

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ARTICLE INFO

Article history:
Received 4 November 2014
Accepted 25 November 2015

Keywords:
Gait
Inertial sensor
Total hip arthroplasty
Outcome assessment
PROM
WOMAC

ABSTRACT

Background: Functional outcome assessment after total hip arthroplasty often involves subjective patient-reported outcome measures whereas analysis of gait is more objective. The study's aims were to compare subjective and objective functional outcomes after total hip arthroplasty between patients with low and high self-reported levels of pre-operative physical function.

Methods: Patients undergoing total hip arthroplasty (n = 36; m/f = 18/18; mean age = 63.9; SD = 9.8 years; BMI = 26.3; SD = 3.5) were divided into a low and high function subgroup, and prospective measures of WOMAC (Western Ontario and McMaster Universities Osteoarthritis Index) function score and gait were compared at baseline and 3 and 12 months post-operatively.

Findings: WOMAC function scores significantly improved in both low and high function subgroups at 3 months post-operatively whereas gait parameters only improved in patients with a low pre-operative function. Between 3 and 12 months post-operatively, WOMAC function scores had not significantly further improved whereas several gait parameters significantly improved in the low function group. WOMAC function scores and gait parameters were only moderately correlated (Spearman's r = 0.33–0.51).

Interpretation: In a cohort of patients undergoing total hip arthroplasty, pre-operative differences in mean WOMAC function scores and gait parameters between low and high function subgroups disappeared by 3 months post-operatively. Gait parameters only improved significantly during the first 3 post-operative months in patients with a low pre-operative function, highlighting the importance of investigating relative changes rather than the absolute changes and the need to consider patients with high and low functions separately.

1. Introduction

Total hip arthroplasty (THA) is one of the most frequently performed and successful reconstructive procedures in orthopedic surgery, with more than one million procedures undertaken every year worldwide (Pivec et al., 2012). Because of an ageing population and the increase in obesity, the incidence of osteoarthritis (OA) and the number of THAs is expected to increase substantially in future decades (Kurtz et al., 2007). Although the majority of THAs are provided to patients aged 65 years and older, the proportion of patients younger than 65 years is projected to increase to 50% of all arthroplasties by 2030 (Kurtz et al., 2009). With a growing and more active older population, and an increasing number of younger patients undergoing THA, the functional demands expected of THA will change and assessment of outcomes will equally need to evolve (Kurtz et al., 2009; Learmonth et al., 2007). Assessment of outcomes after THA often involves patient-reported outcome measures (PROMs) focusing mainly on two domains: pain and function. PROMs are widely used in research and clinical settings, and they are considered easy to use, inexpensive and time efficient. One of the most commonly used PROMs is the disease-specific Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) which has been validated for use with patients undergoing THA (Gandhi et al., 2009; Salaffi et al., 2003). Following THA, patients who are more satisfied are also more likely to have higher total WOMAC scores with the amount of improvement depending on baseline status (Quintana et al., 2012). Furthermore, it has been demonstrated that patients with lower pre-operative self-reported WOMAC function scores do not improve their final outcomes to the same magnitude as patients with higher pre-operative scores (Lavernia et al., 2009). However, WOMAC scores represent subjective self-reported measures

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http://dx.doi.org/10.1016/j.clinbiomech.2015.11.014

which are easily influenced by socioeconomic or psychological factors and dominated by pain (Terwee et al., 2006; Vissers et al., 2012). Moreover, as with many orthopedic PROMs, the WOMAC score suffers from a ceiling effect as it has a limited maximum value that is reached by a substantial proportion of patients who report no pain or functional limitations after THA (Sariali et al., 2014; Uttl, 2005; Wang et al., 2009). A consequence of this ceiling effect is that the true extent of patients' post-operative functional abilities cannot be determined. Therefore, it is important that research considers other methods of assessing functional outcomes after THA. Gait analysis has widely been accepted as an objective measure of physical function, allowing researchers and clinicians to better understand biomechanical alterations in the presence of hip osteoarthritis (OA) and to evaluate the functional success of THA and rehabilitation strategies (Lugade et al., 2010; Ornetti et al., 2010; Sariali et al., 2014). However, the gold standard for clinical gait analysis, an optoelectronic motion capture (MOCAP) system, is time consuming and expensive, requires a specially equipped laboratory and it is limited to a specific motion capture volume, constrained by space and equipment. As an alternative to these sophisticated but clinically unfeasible MOCAP systems, ambulant accelerometers have developed into reliable tools for the assessment of basic spatiotemporal gait parameters (e.g. cadence, step length) which can discriminate healthy subjects from OA patients (Constantinou et al., 2014; Ornetti et al., 2010) and have demonstrated responsiveness to post-operative changes (Senden et al., 2011). More recently, inertial sensors (i.e. accelerometer combined with a gyroscope) have been validated for kinematic measurements of gait (Bugane et al., 2014; Seel et al., 2014), such as joint range of motion (RoM), and could provide more detailed information on gait disturbances in hip OA patients outside the gait laboratory (Bolink et al., 2015a). Given the differences in self-reported functional outcomes between patients with low and high pre-operative function, it is important to establish if these patterns of recovery are also observed with objective measures of physical function (Kennedy et al., 2006; Roder et al., 2007).

The primary aim of the study was to compare the longitudinal changes in physical function between hip OA patients with a low and high self-reported level of physical function, from just prior to THA until one year post arthroplasty, assessed by a subjective patient-reported outcome measure (WOMAC function score) and an objective functional measurement (inertial sensor based gait analysis). A second aim of the study was to compare the trajectories of post-operative recovery between the WOMAC function score and gait parameters. The third aim was to compare the outcomes of gait analysis one year after THA from our cohort with those of a healthy control group. We expected that patients with a low pre-operative WOMAC function score would also demonstrate worse post-operative WOMAC function scores (Lavernia et al., 2009), but hypothesized that these differences may not be found with objective gait parameters as they are less influenced by socioeconomic and psychological factors (Vissers et al., 2012) and weak to moderate correlations between PROMs and performance-based tests have been reported in the literature (Bolink et al., 2015b; Gandhi et al., 2009; Senden et al., 2011; Terwee et al., 2006; Unnanuntana et al., 2012). We further hypothesized that WOMAC function scores and gait parameters would demonstrate distinct post-operative recovery patterns, as for WOMAC function scores a larger change in the first 3 months and a smaller change in the following 9 months was anticipated because they are more likely influenced by ceiling effects (Terwee et al., 2006; Vissers et al., 2012). Finally, we hypothesized that gait performance in patients one year after THA would still be slightly worse compared to healthy controls (Kolk et al., 2014).

2. Methods

2.1. Study and participants

The patient data used in this analysis were from a single centre prospective UK cohort study comparing functional measures in patients undergoing joint replacement (the ADAPT study). A detailed description has been reported previously (Wylde et al., 2012). From this cohort, patients listed for primary THA were selected. Patients completed the WOMAC questionnaire and their gait was assessed pre-operatively (mean = 24 days; SD = 13 days), at 3 months (mean = 106 days; SD = 19 days) and at 12 months (mean = 385 days; SD = 22 days) post-operatively. Patients with missing data at any assessment time, either from the WOMAC questionnaire or from gait analysis, were excluded from this analysis. This resulted in a study population of 36 patients (m/f = 18/18; mean age = 63.9; SD = 9.8 years; BMI = 26.3; SD = 3.5). A control group of individuals (n = 30; m/f = 18/12; mean age = 61.0 years; SD = 5.6; mean BMI = 24.8; SD = 2.8) without joint pain and without a medical history of lower extremity joint surgery was used to compare post-operative outcomes (Bolink et al., 2012).

2.2. Patient-reported outcome assessment

The WOMAC score is designed to provide information on a patient's perception of pain (5 items), stiffness (2 items) and physical function (17 items). The function dimension of the total WOMAC score (i.e. WOMAC function score) was used in this analysis. The WOMAC function score contains 17-items and each item is scored on a 5-point ordered response scale. The score was transformed to a 0–100 score, with 0 representing the lowest (i.e. worst) score and 100 representing the highest (i.e. best) score (Unnanuntana et al., 2012).

2.3. Gait test protocol

Participants were invited to walk 20 m along a straight flat corridor at their own preferred speed (Bolink et al., 2012; Motyl et al., 2013). A 3D inertial sensor (41 × 63 × 24 mm; 39 g; Microstrain Inertia Link) was used, containing gyroscopes (±300°/s) and accelerometers (±5 g) along orthogonal axes in frontal, sagittal and transverse plane. The sensor was attached onto the skin with a neoprene strap, and positioned centrally between the posterior superior iliac spines (PSIS) overlying S1 (Bolink et al., 2012). Via a wireless Bluetooth connection, data from the sensor were stored onto a PC with a sampling frequency of 100 Hz. Data analysis was performed using algorithms in Matlab2009a to detect heel strike (HS) events during gait from the raw antero-posterior (AP) acceleration signal to derive spatiotemporal gait parameters (Gonzalez et al., 2010), including 1) walking speed ($\frac{\text{distance covered}}{\text{time}}$; m/s), 2) cadence ($60 * \frac{\text{step count}}{\text{time}}$; steps/min), 3) step time (s), 4) step length ($\frac{\text{distance covered}}{\text{step count}}$; m); 5) step time irregularity ($\frac{\text{SD}}{\text{mean}}$; coefficient of variance) and 6) step time asymmetry ($100\% * \frac{(\text{abs}(\text{left step times} - \text{right step times}))}{(0.5 * (\text{left step times} + \text{right step times}))}$; %) (Bolink et al., 2012). The sensor's inbuilt integration of the gyroscope signals provided static and dynamic orientation angles, allowing additional kinematic characterization of the pelvis during gait. The range of motion (RoM; degrees) of the pelvis in frontal plane (i.e. pelvic obliquity) was calculated (Bolink et al., 2012) as it is related to impairment of hip abductor muscles in patients with hip OA (Lenaerts et al., 2009; Rasch et al., 2010; Watelain et al., 2001) which may persist following THA (Perron et al., 2000).

2.4. Statistical analysis

Pre-operative WOMAC function score was dichotomized according to median threshold to define low and high function groups. Linear mixed models (LMMs) in Stata13 were used to investigate longitudinal trends of changes post-operatively in the low and high function groups with *P*-values <0.05 as significance threshold. Self-reported WOMAC function scores and objective gait measures are described for each measurement point with median and interquartile range (IQR), between 25th and 75th percentile, because of the non-normal distribution of the post-operative data. Comparison of both self-reported WOMAC function scores and gait measures between low and high function groups was conducted with Mann–Whitney U tests. Linear mixed models with random intercept and slope (on period's indicators) were used to assess the magnitudes of change between pre-operative and 3 months post-operative, and between 3 and 12 months post-operative. These changes were normally distributed and results are reported by the mean and 95% confidence interval (CI). The magnitudes of change (i.e. slope of curve) for WOMAC function scores and gait parameters between the first 3 post-operative months and the following 9 post-operative months were quantified as averaged change per month (mean; 95% confidence interval; P-value) and outcomes were compared between low and high function groups within the LMM framework. Correlations between WOMAC function scores and gait parameters were calculated with the Spearman's correlation coefficient and interpreted as follows: <0.2: none; 0.21–0.5 weak; 0.51–0.8: moderate; >0.81: strong (Gudbergsen et al., 2013).

3. Results

Pre-operatively, the median WOMAC function score was 49 (IQR = 36–71). Using this median as a cut-off, two subgroups were formed: a low function group (n = 18) with a pre-operative median WOMAC function score of 36 (IQR = 22–41) and a high function group (n = 18) with a significantly higher pre-operative median WOMAC function score of 71 (IQR = 65–82) ($P < 0.001$). In gait, significant differences were also found between the low and high function groups for the parameters speed (0.89 vs. 1.10 m/s; $P = 0.006$), step length (0.50 vs. 0.60 m; $P = 0.003$) and RoM pelvic obliquity (4.7 vs. 6.0°; $P = 0.015$) (Table 1). In addition, significant but weak to moderate correlations were found between the pre-operative WOMAC function scores and gait parameters speed (Spearman's r = 0.51; $P = 0.002$), step length (Spearman's r = 0.47; $P = 0.004$) and RoM (Spearman's r = 0.43; $P = 0.010$) (Table 2).

At 3 months post-operatively, WOMAC function scores had significantly improved for the total patient group (median = 92; IQR = 81–96; $P < 0.001$), for the low function group (median = 91; IQR = 79–96; $P < 0.001$) and high function group (median = 91; IQR = 84–99; $P < 0.001$); (Table 1; Fig. 1). Furthermore, 18 of 36 patients (50%) reached near-maximum (≥90) WOMAC function scores at 3 months post-operatively (Fig. 1). No significant difference in WOMAC function score was observed between the low function group and the high function group at 3 months post-operatively. The magnitude of change for WOMAC function scores during the first 3 post-operative months was significantly higher for patients from the low function group compared to patients from the high function group (averaged change per month = 13.31 vs. 3.59 points respectively; $P < 0.001$; Table 3). Gait parameters in the total patient group had also improved significantly 3 months after THA, except for step time irregularity and step time asymmetry (Table 1). Sub group analysis demonstrated that the gait parameters only significantly improved in patients from the low function group and comparing the magnitudes of change (i.e. averaged change per month) during the first 3 post-operative months between the low and high function group demonstrated significant differences for the gait parameters: speed (0.060 vs. 0.011 m/s resp.; $P = 0.007$), cadence (2.64 vs. 0.35 steps/min resp.; $P = 0.03$), step time (−0.019 vs. −0.002 s resp. $P = 0.039$), step length (0.023 vs. 0.04 m resp.; $P = 0.009$) and RoM (0.43 vs. 0.18° resp.; $P = 0.008$) (Fig. 1, Table 3). At 3 months post-operatively, patients from the low function group reached a level of walking ability comparable to patients from the high function group as median values of gait parameters were not significantly different anymore. No significant correlation for any of the gait parameters with WOMAC function score was found at 3 months post-operatively (Table 2).

At 12 months post-operatively, WOMAC function scores were not significantly different to WOMAC function scores measured at 3 months post-operatively in the total group, nor in the low and high function groups (Table 1). In addition, 23 of 36 patients (64%) reached near-maximum (≥90) WOMAC function scores and 10 of 36 patients (28%) reported the maximum WOMAC function score of 100 at 12 months post-operatively. Between 3 and 12 months post-operatively, speed and step length significantly improved in the total patient group (Table 1; Fig. 1). Separate subgroup analysis demonstrated that the observed improvement was only found in patients with a low pre-operative self-reported function. However, no differences were found for gait parameters at 3 and at 12 months post-operatively between the high and low function groups (Table 1) and the averaged change per month between 3 and 12 months post-operatively showed no significant differences between the low and high function groups (Table 2). At 12 months post-operatively, weak correlations were found between the WOMAC function score and the gait parameters speed (Spearman's r = 0.45; $P = 0.005$), cadence (Spearman's r = 0.37; $P = 0.027$), step time (Spearman's r = 0.37; $P = 0.027$), RoM (Spearman's r = 0.51; $P = 0.002$), step time irregularity (Spearman's r = −0.39; $P = 0.018$) and step time asymmetry (Spearman's r = −0.33; $P = 0.047$). At 12 months post-operatively, the THA cohort approached the level of the control group comparing gait parameters, except for speed (1.20 vs. 1.29 m/s; $P = 0.036$) and step length (0.64 vs. 0.68 m; $P = 0.004$) (Table 1).

4. Discussion

The primary aim of this study was to compare physical function after THA between patients with a low and high self-reported level of pre-operative physical function, by subjective self-reported WOMAC function scores and objective inertial sensor based gait analysis. Although it has been demonstrated that the post-operative outcomes of patients with lower pre-operative WOMAC function scores do not improve to the same magnitude as patients with higher pre-operative scores (Lavernia et al., 2009), it was hypothesized that these differences in functional outcome may not be found with objective measures of gait. To address this hypothesis, the study's cohort was divided into a low and a high function group using the median of the pre-operative WOMAC function score (i.e. 49) as a cut-off. These self-reported levels of physical function are in comparison with the findings of previous studies by Unnanuntana et al. (2012) and Mahomed et al. (2002) which reported mean pre-operative WOMAC function scores of 48.5 and 46 respectively in their cohorts of pre-operative THA patients. In the current study, patients with lower pre-operative WOMAC function scores also performed significantly worse on gait pre-operatively; they walked slower, with smaller steps and less RoM. However, only weak to moderate correlations (Spearman's r range 0.43–0.51) were found between pre-operative WOMAC function scores and pre-operative gait parameters. These findings concur with the results from the study by Unnanuntana et al. (2012), which reported a Spearman's correlation coefficient of 0.54 between pre-operative WOMAC function scores and a 2-minute walk test. Findings from our study and previous research suggest that WOMAC and gait capture a different dimension of physical function.

Our study's main finding was that the significant differences in pre-operative WOMAC function scores and gait parameters between low and high function groups are not found at 3 and 12 months after THA. Patients with a low pre-operative level of physical function seem to experience more functional limitations in relation to OA and have more functional improvement to gain from surgery. Post-operatively, they improve significantly more on both subjective self-reported WOMAC function scores and objective gait parameters, and reach mean functional outcomes comparable to patients with better pre-operative function. Therefore, in the analysis of functional recovery after THA, our findings suggest that it is important to differentiate a cohort into subgroups and look at the relative changes instead of focusing solely on absolute changes. In addition, our findings on functional recovery after THA are in marked contrast to pain based outcomes, where a pre-operative

Table 1
Outcomes of WOMAC function score and gait parameters for the total patient group and sub groups with a low pre-operative WOMAC function score (below median) and a high pre-operative WOMAC function score (above median). IQR = interquartile range.

Outcome parameters		Pre-operative		Low vs High	3 months			Low vs High	12 months			Low vs. High	Control group n = 30		
		Median	IQR	*P*-value	Median	IQR	*P*-value	*P*-value	Median	IQR	*P*-value	*P*-value	Median	IQR	*P*-value
WOMAC function (0–100)	Total	48.5	35.5–71.3	<0.001	91.2	81–95.6	<0.001	0.53	95.6	83.8–100	0.44	0.44			
	Low function	35.5	22.1–41.1		90.9	79.4–95.6	<0.001		94.1	83.8–98.5	0.89				
	High function	71.3	64.7–82.4		91.2	83.8–98.5	<0.001		96.3	85.9–100	0.24				
Speed (m/s)	Total	0.97	0.81–1.12	0.006	1.12	0.96–1.30	<0.001	0.45	1.20	1.08–1.33	<0.001	0.69	1.29	1.14–1.41	0.036
	Low function	0.89	0.71–0.97		1.10	0.92–1.30	<0.001		1.20	1.09–1.33	0.001				
	High function	1.10	0.97–1.24		1.16	0.98–1.36	0.28		1.23	1.07–1.34	0.055				
Cadence (steps/min)	Total	106.0	98.4–113.9	0.27	110.5	102.3–117.3	0.008	0.57	112.7	107.3–119.3	0.056	0.20	111.6	105.4–116.3	0.54
	Low function	103.8	92.0–116.3		113.7	100.8–117.7	0.007		114.4	109.8–122.5	0.069				
	High function	108.0	99.6–111.4		110.2	106.8–115.2	0.41		110.6	102.7–116.7	0.42				
Step time (s)	Total	0.57	0.53–0.61	0.27	0.54	0.51–0.59	0.020	0.57	0.53	0.50–0.56	0.11	0.20	0.54	0.52–0.57	0.66
	Low function	0.58	0.52–0.65		0.53	0.51–0.60	0.020		0.52	0.49–0.55	0.20				
	High function	0.56	0.54–0.60		0.55	0.52–0.56	0.48		0.54	0.51–0.59	0.35				
Step length (m)	Total	0.54	0.48–0.62	0.003	0.60	0.53–0.68	<0.001	0.22	0.64	0.57–0.70	<0.001	0.17	0.68	.63–0.75	0.004
	Low function	0.50	0.45–0.55		0.58	0.52–0.67	<0.001		0.61	0.55–0.67	0.001				
	High function	0.60	0.53–0.68		0.63	0.55–0.70	0.37		0.66	0.58–0.73	0.062				
RoM (°)	Total	5.7	3.6–6.3	0.015	6.4	5.3–7.9	<0.001	0.57	7.5	5.5–8.4	0.014	0.97	7.3	5.9–8.9	0.12
	Low function	4.7	3.2–6.0		6.3	5.0–7.7	<0.001		7.2	6.0–8.4	0.010				
	High function	6.0	5.3–7.5		6.4	5.8–8.0	0.10		7.7	5.0–8.4	0.051				
Step irregularity (CV)	Total	0.05	0.03–0.07	0.68	0.05	0.03–0.06	0.65	0.38	0.04	0.03–0.06	0.26	0.55	0.03	0.02–0.04	0.37
	Low function	0.05	0.04–0.07		0.04	0.03–0.07	0.40		0.04	0.03–0.06	0.44				
	High function	0.06	0.03–0.07		0.05	0.04–0.06	0.60		0.05	0.03–0.06	0.42				
Step asymmetry (%)	Total	4.75	1.78–7.82	0.47	2.92	1.58–7.05	0.34	0.15	2.67	0.88–5.51	0.93	0.66	3.28	1.81–5.77	0.87
	Low function	5.97	2.05–8.00		2.20	1.58–4.67	0.28		3.18	0.70–5.23	0.88				
	High function	3.46	1.58–7.45		5.99	2.03–7.69	0.71		2.38	1.34–5.92	0.85				

Table 2
Spearman correlation coefficients (r) between WOMAC function score and gait parameters with corresponding *P*-values.

	WOMAC function score					
	Pre-operative		3 months		12 months	
	r	*P*-value	r	*P*-value	r	*P*-value
Speed	0.51	0.002	0.31	0.071	0.45	0.005
Cadence	0.31	0.062	0.24	0.158	0.37	0.027
Step time	−0.31	0.062	−0.24	0.158	−0.37	0.027
Step length	0.47	0.004	0.25	0.134	0.32	0.059
RoM	0.43	0.010	0.14	0.422	0.51	0.002
Step time irregularity	−0.06	0.717	−0.26	0.119	−0.39	0.018
Step time asymmetry	−0.11	−0.530	0.06	0.741	−0.33	0.047

score is usually a strong predictor of post-operative outcome (Terwee et al., 2006; Vissers et al., 2012). Composite pain and function scores behave like pain scores in predicting outcome (Terwee et al., 2006) which argues for pain and function to be measured separately as distinct domains.

The second aim of this study was to compare the trajectories of post-operative recovery between WOMAC function scores and gait parameters and it was hypothesized that WOMAC function scores would demonstrate a larger change in the first 3 months and a smaller change in the following 9 months due to ceiling effects. A ceiling effect occurs when the test is relatively easy and a substantial proportion of participants reach either maximum or near-maximum scores (Uttl, 2005) and when this proportion is larger than 20% at one occasion during longitudinal follow-up (Wang et al., 2009). In this study's cohort, 18 of 36 patients (50%) reached near-maximum (≥90) WOMAC function scores at 3 months post-operatively, 23 of 36 patients (64%) reached near-maximum (≥90) WOMAC function scores at 12 months post-operatively and 10 of 36 patients (28%) reached the maximum score (i.e. 100) at 12 months post-operatively. Due to this ceiling effect, further functional improvement will not be captured by the WOMAC function score and the true extent of a patient's functional abilities cannot be determined. In contrast, objective measures of function by gait analysis demonstrated sensitivity to post-operative improvement beyond 3 months follow-up for three main gait parameters (i.e. speed, step length and RoM); but no further improvements were found for cadence, step time, asymmetry and irregularity. This may be due to inaccuracy of the algorithm to measure heel strike events precisely, as literature reports mean timing errors of 13 ms (SD = 35 ms) for heel strike measurements with this specific algorithm compared to force plate measurements (Gonzalez et al., 2010). These timing errors are slightly larger than values reported by Dijkstra et al. (2010) (mean = 6 ms; SD = 16 ms) although the mean error difference is within one sampling period (10 ms). Nonetheless, the inaccuracy of the algorithm could have influenced our study results for all spatiotemporal gait parameters as small improvements were found to be significant between pre-operative status and 3 months after THA (e.g. step time: 30 ms improvement for the total patient group) and for the difference in magnitude of improvement between low and high function groups (e.g. step time: 17 ms difference in improvement). In addition, the observed improvement of gait parameters between pre-operative status and 3 months after THA, and between 3 and 12 months after THA, was only found in patients with a low pre-operative function. In the high function group, none of the gait parameters demonstrated a significant ($P < 0.05$) improvement during follow-up. This may be due to the small subgroup size (n = 18) which lacks power for the minor gait improvements that were observed in the high function patient group to become statistically significant. Another explanation for the lack of significant post-operative changes for gait parameters in the high function group could be that gait is a low demand task in comparison to other activities of daily living, which may be better discriminators of outcome for those with high pre-operative function. Normal gait is also a main rehabilitation goal in the early post-operative stage, therefore practised extensively and thus likely to improve quickly (Rasch et al., 2010). Challenging physical tasks may have higher sensitivity as a tool to identify remaining functional disabilities post-operatively (Shrader et al., 2009). For gait, variation of walking speed (e.g. preferred speed vs. high speed) could provide a bigger challenge (Landry et al., 2007). Other physically more demanding performance-based tests, such as timed get-up-and-go (TUG), six minute walk test (6MWT) and stair climbing test (SCT) could be used as an alternative to the objective functional test described in this study (Hjorth et al., 2014; Stevens-Lapsley et al., 2011).

The third aim of this study was to compare the outcomes of gait analysis one year after THA from our cohort with those of a healthy control group without lower limb OA or previous lower limb surgery, and we hypothesized that gait performance after THA would still be slightly worse than in healthy controls (Kolk et al., 2014). Our results demonstrated that by 12 months post-operatively, patients with a THA had nearly reached the level of the control group in gait performance, except for the parameters speed and step length. At 12 months after THA, patients seem to walk with a similar step frequency compared to healthy controls but with smaller steps and consequently lower speed. These findings are in accordance to the results of a meta-analysis by Ewen et al. (2012) including 7 studies comparing gait between patients >6 months after THA and a control group. Across these studies, the mean walking speed for the patient groups and control groups ranged from 0.707–1.31 m/s and 0.921–1.34 m/s respectively, and 3 studies reported significantly lower walking speed for their patient group compared to their control group. Furthermore, 6 studies reported stride length and 4 of these studies reported a significant reduction in stride length for their patient group compared to their control group. A more recent systematic review by Kolk et al. (2014) describes the results from 28 studies comparing gait between patients after THA and a control group, including the 7 studies from the meta-analysis by Ewen et al. (2012), and demonstrates that walking speed was not different from controls in most studies that had a short (6–9 months) follow-up period, whereas it was lower than controls in most of the studies that had a follow-up of 24 months or longer. This coincided with a reduction in step length in the long-term follow-up studies, which was generally not found in the short-term follow-up studies. In our current study, the patient group demonstrated a median walking speed of 1.20 m/s at 12 months follow-up which was significantly lower than our control group with a median walking speed of 1.29 m/s ($P = 0.036$). Furthermore, step length was also significantly reduced in our patient population at 12 months follow-up compared to our control group (0.64 m vs. 0.68 m; $P = 0.004$).

Limitations of the study should be acknowledged when interpreting the results. Although the inclusion of multiple assessment times is a strength, the assessment of function at 3 and 12 months post-operatively may not capture the full extent of post-operative changes in physical function. As most of the functional improvement was demonstrated within 3 months post-operatively for WOMAC function scores and for gait parameters, earlier follow-up measures (e.g. six weeks post-operatively) could provide more insight in recovery and guide early individual rehabilitation (Senden et al., 2011). In order to capture improvement of physical function beyond 12 months post-operatively and in patients with high pre-operative function, we advocate combining gait analysis with more high demand tasks. Another limitation of our study is the inaccuracy of the algorithm that was used to detect heel strikes and to derive spatiotemporal gait parameters. Small timing errors could have influenced their outcomes and therefore our study results. Furthermore, only patients undergoing primary THA were included in the analysis and patients that did not complete all the assessments were excluded. Consequently, our small study population limits the conclusions that can be drawn. However, the study was exploratory in nature and generated findings that can be investigated further.

5. Conclusion

This study indicates that in a cohort of patients undergoing THA, pre-operative differences in mean WOMAC function scores and gait parameters between low and high function subgroups have disappeared by 3 months post-operatively. Therefore, it may be important to look at the relative changes rather than the absolute changes only. Furthermore, assessment of physical function by self-report showed

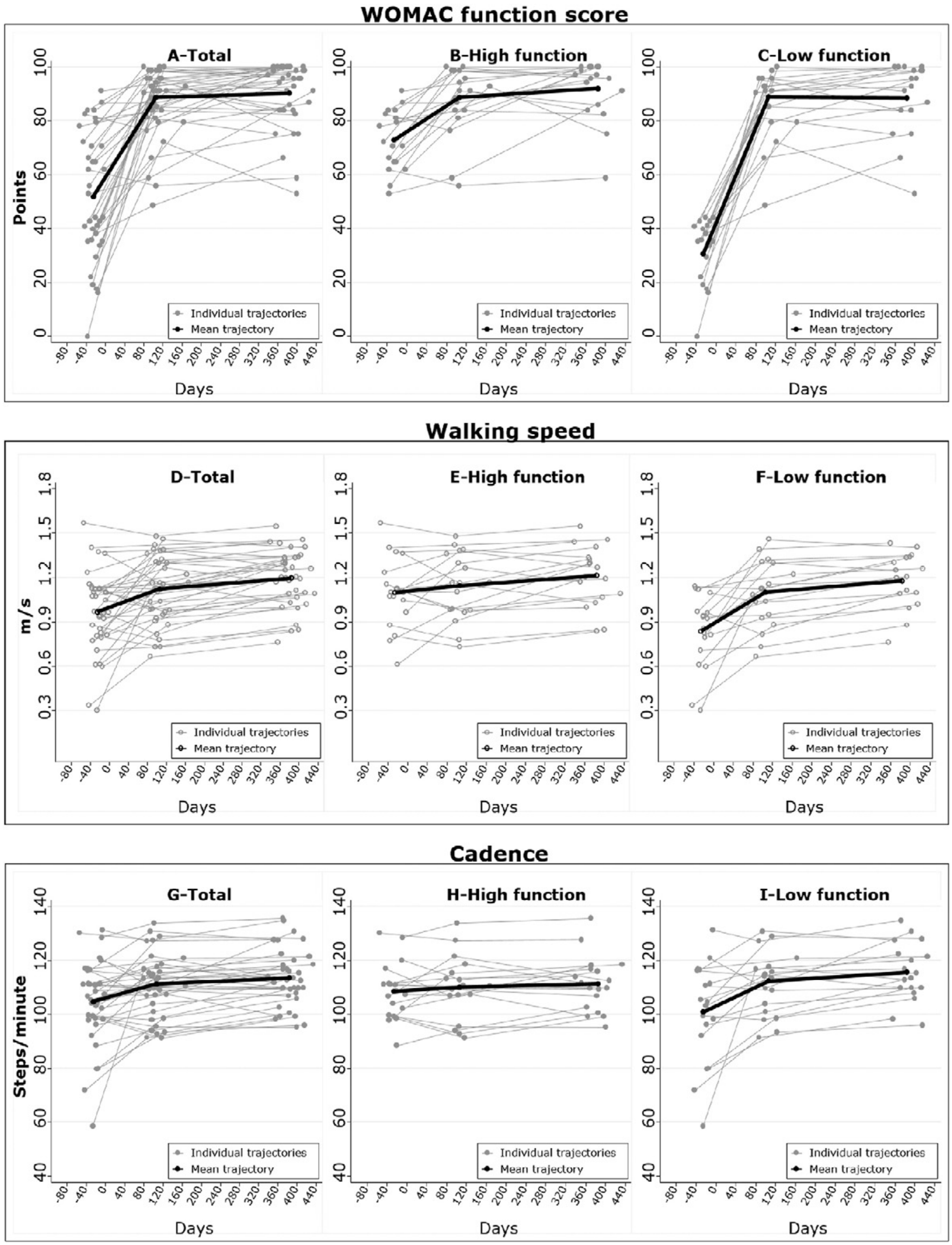

Fig. 1. A–X: Individual (grey) and mean (black) trajectories for measures of WOMAC function score (A = total group, B = high function group, C = low function group), walking speed (D = total group, E = high function group, F = low function group), cadence (G = total group, H = high function group, I = low function group), RoM (J = total group, K = high function group, L = low function group), step time (M = total group, N = high function group, O = low function group), step length (P = total group, Q = high function group, R = low function group), step irregularity (S = total group, T = high function group, U = low function group) and step asymmetry (V = total group, W = high function group, X = low function group) during longitudinal follow-up.

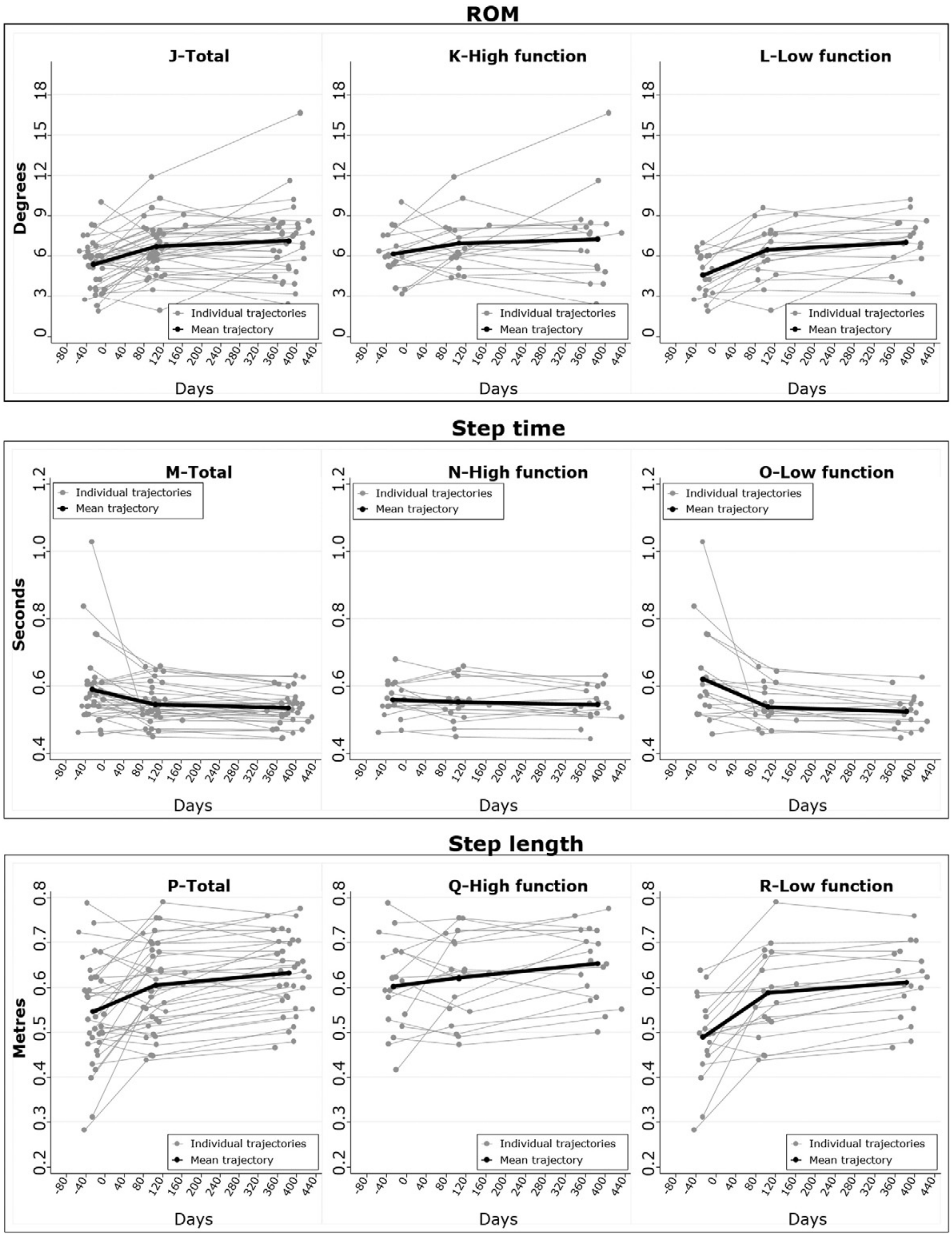

Fig. 1 (*continued*).

marked improvement in the first 3 months after surgery with little further improvement thereafter, whereas gait analysis showed a more gradual improvement over 12 months with sensitivity to capture improvement beyond 3 months after THA. The weak to moderate correlations between both methods suggest that they measure slightly different aspects of functional recovery and can be supplementary to each other.

Acknowledgements

This article presents independent research funded by the National Institute for Health Research (NIHR) under its Programme Grants for Applied Research programme (RP-PG-0407-10070). The views expressed in this article are those of the authors and not necessarily those of the NHS, the NIHR or the Department of Health. The research

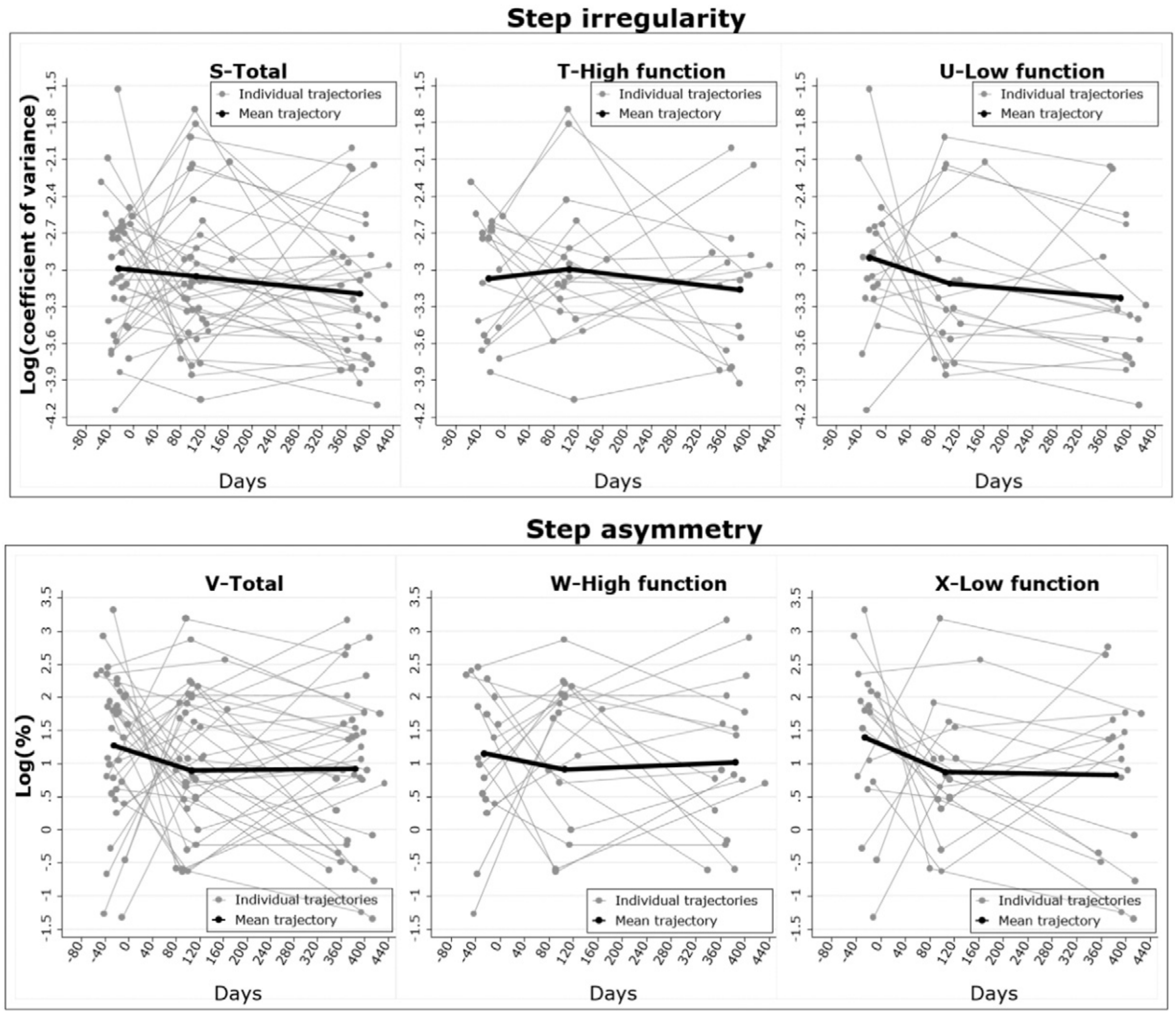

Fig. 1 (*continued*).

Table 3
Averaged change per month during the first 3 post-operative months and the following 9 post-operative months, comparing the low function group with the high function group. CI = confident interval.

Averaged change per month		Pre-operative—3 months			Low vs high	3 months—12 months			Low vs high
		Mean	CI (95%)	*P*-value	*P*-value	Mean	CI (95%)	*P*-value	*P*-value
WOMAC function score (0–100)	Total	8.45	6.36–10.54	<0.001	<0.001	0.17	−0.26 to 0.59	0.44	0.34
	Low function	13.31	11.08–15.55	<0.001		−0.039	−0.62 to 0.54	0.89	
	High function	3.59	2.10–5.08	<0.001		0.37	−0.25 to 1.00	0.24	
Speed (m/s)	Total	0.035	0.016–0.055	<0.001	0.007	0.008	0.004–0.012	<0.001	0.86
	Low function	0.060	0.030–0.091	<0.001		0.008	0.003–0.013	0.001	
	High function	0.011	−0.009 to 0.030	0.28		0.008	0–0.014	0.28	
Cadence (steps/min)	Total	1.50	0.39–2.60	0.008	0.03	0.24	−0.01 to 0.49	0.056	0.39
	Low function	2.64	0.71–4.58	0.007		0.35	−0.03 to 0.73	0.069	
	High function	0.35	−0.48 to 1.17	0.41		0.13	−0.19 to 0.45	0.42	
Step time (s)	Total	−0.010	−0.002 to −0.019	0.02	0.039	−0.001	−0.002 to 0	0.11	0.67
	Low function	−0.019	−0.035 to −0.003	0.02		−0.001	−0.004 to 0.001	0.19	
	High function	−0.002	−0.003 to 0	0.48		−0.001	−0.003 to 0.001	0.35	
Step length (m)	Total	0.013	0.006–0.02	<0.001	0.009	0.003	0.001–0.004	<0.001	0.57
	Low function	0.023	0.013–0.033	<0.001		0.002	0.001–0.004	0.001	
	High function	0.004	−0.005 to 0.014	0.37		0.003	0.001–0.006	0.012	
RoM (°)	Total	0.31	0.16–0.45	<0.001	0.08	0.046	0.015–0.108	0.014	0.70
	Low function	0.43	0.25–0.62	<0.001		0.059	−0.012 to 0.129	0.010	
	High function	0.18	−0.04 to 0.40	0.10		0.034	0.068–0.137	0.051	
Step irregularity log(CV)	Total	−0.015	−0.08 to 0.05	0.65	0.32	−0.015	−0.04 to 0.01	0.26	0.82
	Low function	−0.049	−0.164 to 0.056	0.40		−0.012	−0.043 to 0.019	0.44	
	High function	0.019	−0.051 to 0.088	0.60		−0.018	−0.062 to 0.026	0.42	
Step asymmetry log(%)	Total	−0.086	−0.263 to 0.091	0.34	0.73	0.003	−0.062 to 0.068	0.93	0.81
	Low function	−0.118	−0.334 to 0.098	0.28		−0.005	−0.069 to 0.059	0.88	
	High function	−0.055	−0.341 to 0.232	0.85		0.011	−0.104 to 0.125	0.85	

team acknowledges the support of the NIHR, through the Comprehensive Clinical Research Network.

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