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Original Article

Reliability of kinematic waveforms during gait analysis with total hip arthroplasty patients

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ABSTRACT

Purpose: The aim of the study was to determine the test-retest reliability of lower limb kinematic waveforms derived from 3D gait analysis (3DGA) in patients following total hip arthroplasty (THA).
Methods: Eight (7 M:1F; age: 70 ± 7 years; height: 1.68 ± 0.11 m; mass: 85 ± 20 kg) adults with a unilateral THA attended test and retest sessions. 3DGA was undertaken with participants walking at a self-selected pace along a 7 m walkway within each session. The standard error or the measurement (SEM) was calculated for hip, knee and ankle joint angles in all three planes, over the walking gait cycle.
Results: The SEM ranged from 2.9 to 4.1°, 2.7–3.7° and 1.9–3.9°, in the sagittal, frontal and traverse planes at the hip. At the knee the SEM ranged from 1.6 to 4.2°, 1.0–1.9° and 1.3–2.9° in the sagittal, frontal and transverse planes, respectively. While the SEM ranged from 0.7 to 2.0°, 1.2–2.3° and 2.9–4.0° in the sagittal, frontal and transverse planes at the ankle.
Conclusions: The findings demonstrate that 3DGA provides a reliable means of quantifying lower limb kinematics over the walking gait cycle in patients following THA, with all SEM values below the 5° threshold previously suggested to identify clinically meaningful differences. The SEM values reported may aid in the interpretation of changes in lower limb kinematics in patients following THA.

1. Introduction

Three-dimensional gait analysis (3DGA) using infrared marker-based motion capture systems provides the gold standard means of quantifying joint function [1,2]. 3DGA has previously been used to determine how THA influences lower limb kinematic patterns during walking gait [3–6]. Typically, patients following THA are reported to display improved lower limb function during walking, but generally do not achieve normative movement patterns [3–6]. While improvements in lower limb function have been reported post-operatively the magnitude of change is often relatively small [7–9], and as such a greater understanding of the reliability of 3DGA in patients following THA is imperative to ensure changes are true and not potentially due to error inherent within the measurement.

Numerous studies have explored the reliability of 3DGA within asymptomatic populations [10–12] and there are a growing body of literature exploring the reliability of gait analysis in patients with osteoarthritis [13–15]. However, extrapolating reliability metrics from studies on healthy individuals or those with osteoarthritis to patients following THA is inappropriate, as the population assessed is a key factor influencing the reliability of 3DGA [16]. The authors are aware of only one study [16] exploring the reliability of 3DGA in patients following THA. Zűgner et al. [16], reported on the inter-rater reliability of hip joint kinematics in three populations: healthy controls, osteoarthritis and THA groups. The variance between raters was typically greater for the patients following THA compared to controls, but not significantly so. While this study suggests the inter-rater reliability of hip joint kinematics are comparable between THA and asymptomatic populations, test-retest

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reliability was not reported. Furthermore, reliability was inferred from comparisons of standard deviations within the work of Zűgner et al. [16], with selected Bland-Altman plots used to supplement this data.

The need for further work exploring the reliability of 3DGA in clinical populations [17] and moves towards quantifying the absolute rather than the relative reliability [18] has been highlighted previously. Furthermore, with waveform analysis becoming more common when utilising 3DGA [19,20], it is also important to understand the reliability of the kinematic waveform, as opposed to pre-selected discrete variables. As such the aim of the current study was to determine the test-retest reliability of lower limb kinematic waveforms derived from 3DGA within a sample of individuals who had previously undergone THA. Specifically, the SEM associated with three-dimensional hip, knee and ankle joint angles over the walking gait cycle (GC) were quantified in patients following THA. A greater understanding of the reliability of kinematic waveforms within this population should aid researchers and clinicians in their interpretation of 3DGA data reported in both previous and future studies.

2. Materials and methods

2.1. Participants

Eight adults who had previously received a unilateral THA participated in this study (Table 1). Inclusion criteria for the study were unilateral THA for osteoarthritis, at least one-year previously, aged 18 years or above, able to walk at least 10 m barefoot without the use of walking aids. Exclusion criteria were evidence of infection within the THA, knee or ankle osteoarthritis in either limb, total knee arthroplasty, known foot deformities, body mass index over 40, known neurological conditions and/or impaired balance. All participants within the study underwent their surgery through a posterior surgical approach. Prior to testing all participants provided written informed consent and ethical approval was granted by the National Health Service Research Ethics Council (17/LO/1584).

2.2. Procedures

A test-retest research design was used for the study with all participants attending two testing sessions, each lasting roughly 2 h. Typically, 10 days separated trials. Within each testing session, participants walked barefoot along a 7 m walkway, at a self-selected velocity (Fig. 1). Walking velocity was monitored during each trial using SmartSpeed timing gates (Fusion Sport, Brisbane, Australia). Participants completed on average 10 complete trials within each testing session, which were defined as the operated limb landing on the force platform without any noticeable deviations in walking gait. All measurements were undertaken by a single assessor who was a trained physiotherapist (HG) with 5 years' experience of conducting 3DGA.

A seven segment, six-degrees of freedom lower limb model was used to define the pelvis and thighs, shanks and feet of each participant (Fig. 1) [21]. For this study, only data from the operated limb is presented. The pelvis was defined by markers (Ø 9 mm) located on the anterior and posterior superior iliac spines and modelled using the CODA pelvis option within Visual 3D (Version 6.1.18, C Motion, Germantown, MD, USA) [22]. The thigh was defined proximally by the hip joint centre and distally by markers located on the medial and lateral femoral epicondyles. The shank was defined proximally by markers located on the medial and lateral femoral epicondyles, and distally by markers placed on the medial and lateral malleoli. Both the thigh and shank were tracked using a cluster of four non-collinear markers attached to the distal lateral aspect of the segment, in line with the calibrated anatomical system technique [23]. The foot was defined proximally by the medial and lateral malleoli markers and distally by markers placed on the first and fifth metatarsal heads. Additional tracking markers for the foot were placed on the central aspect of the calcaneus and second metatarsal base. The hip joint centre was calculated using regression equations developed by Bell et al. [24], with the knee and ankle joint centres defined as the midpoint between the medial and lateral femoral epicondyles, and the medial and lateral malleoli, respectively. Segmental coordinate systems were oriented as follows; x = medial-lateral, y = anterior-posterior and z = vertical.

Kinematic data were collected using a ten camera Qualisys motion capture system (Oqus 3+, Qualisys, Gothenburg, Sweden) sampling at 200Hz. The motion capture system was calibrated in line with the manufactures guidelines and only calibrations which produced residuals of <0.4 mm were accepted. A short static trial was collected, prior to the collection of dynamic trials, with the participant stood in a relaxed position to enable the relevant segmental co-ordinate systems to be calculated (Fig. 1).

Table 1
Individual patient and group mean descriptive characteristics.

	Age (years)	Height (m)	Mass (kg)	BMI (kg/m^2)	Gender	Time Post-THA (months)
Participant 1	76	1.70	88	30	M	62
Participant 2	64	1.65	62	23	M	15
Participant 3	61	1.71	105	36	M	14
Participant 4	73	1.86	117	34	M	12
Participant 5	71	1.72	83	28	M	13
Participant 6	70	1.65	92	34	M	13
Participant 7	64	1.72	72	24	M	15
Participant 8	81	1.45	62	29	F	30
Mean (SD)	70 (7)	1.68 (0.11)	85 (20)	30 (5)		15 (13–19)[a]

[a] Median and interquartile range.

2.3. Data processing

Five trials per participant were extracted for analysis. Marker trajectories were reconstructed and labelled within Qualisys Track Manager (Version 2.17, Qualisys, Gothenburg, Sweden) and exported as C3D files to Visual 3D. Kinematic data were filtered using a 6Hz Butterworth low pass. Data were time normalised to 101 data points corresponding to 100 % GC duration. Hip, knee and ankle joint angles were calculated using an XYZ ordered cardan sequence.

2.4. Data analysis

The SEM was calculated from the variance components reported by a two-way mixed effect model analysis of variance (ANOVA), in line with the recommendation of Hopkins [25], for each joint in each plane, on a point-by-point basis using a publicly available code developed by Pini et al., [26]. SEM was calculated on both patient and group levels. Patient level analysis was undertaken using the data from each of the 5 processed trials in the test and retest sessions and group level analysis using the average movement pattern for each participant in the test and retest sessions. SEM values were interpreted relative to a 5° clinically meaningful threshold, as error levels above this magnitude have been suggested to have the potential to result in misleading clinical interpretations when utilising 3DGA [17]. Additionally, paired samples *t* tests were used to compare walking velocity, stride length and the time of toe off within the walking GC between test and retest sessions, with the alpha level set to $p < .05$. Cohen's *d* was used as an estimate of effect size when comparing these spatiotemporal parameters between test and retest sessions, and was interpreted as follows: <0.2 trivial, 0.2–0.49 small, 0.5–0.79 medium and 0.8 + large [27]. All data analysis was undertaken within RStudio (Boston, MA, USA).

3. Results

No significant ($p \geq .20$) differences in walking velocity, stride length and the time occurrence of toe off within the GC between test and retest

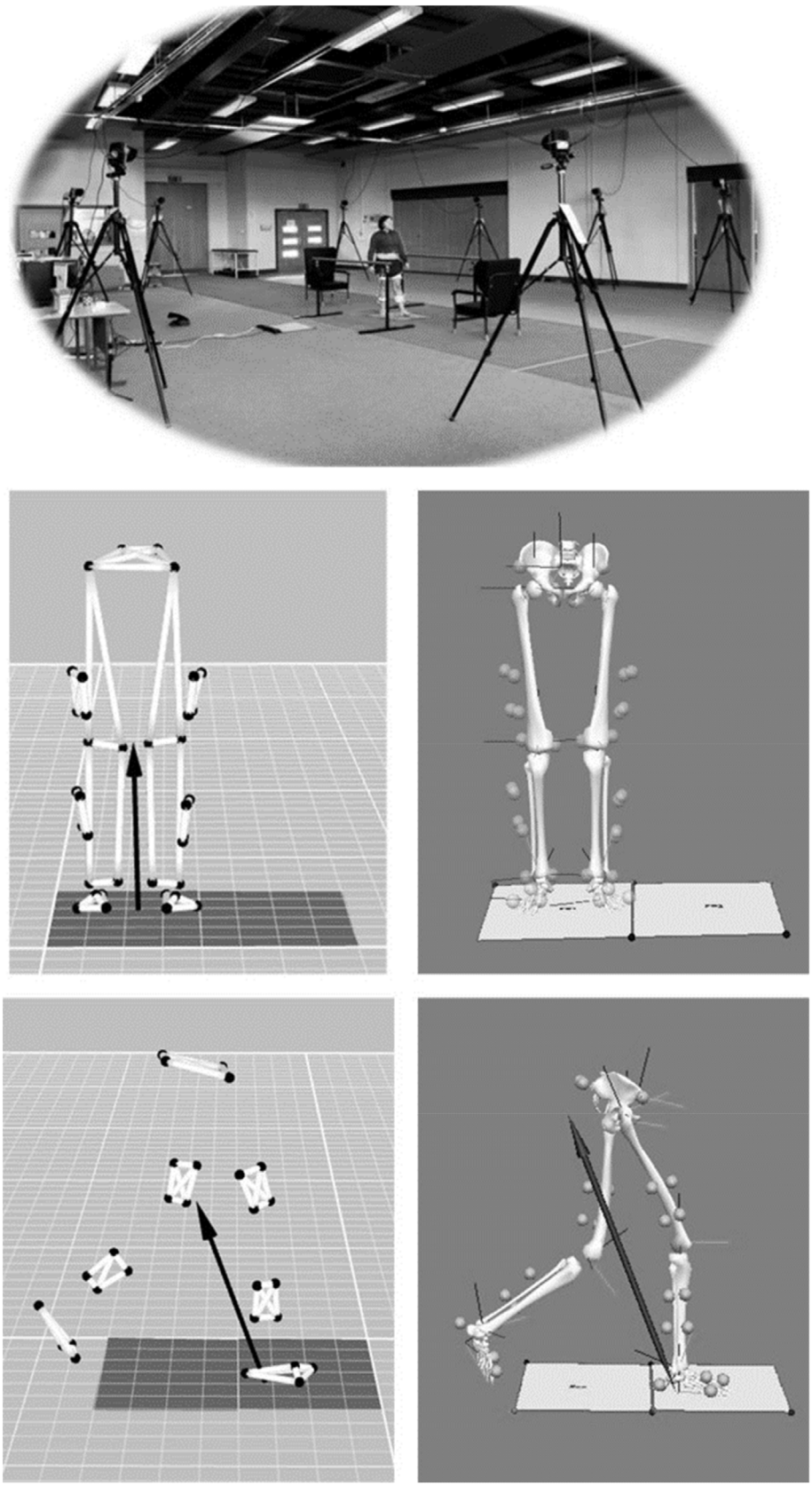

Fig. 1. Example laboratory set up with participant walking through the 3DGA capture volume. Example static and dynamic trials within both Qualisys Track Manager and Visual 3D software.

Table 2
Walking velocity, stride length and the time of toe off between test and retest sessions, with significance (p) and effect size (Cohen's d) values. Mean (SD).

	Test	Retest	p	d
Walking Velocity ($m \cdot s^{-1}$)	1.16 (0.34)	1.19 (0.35)	.20	0.07
Stride Length (m)	1.24 (0.28)	1.24 (0.30)	.64	0.11
Time of Toe Off (GC%)	60 (2)	60 (2)	.84	0.01

sessions were reported, with all differences associated with trivial effect sizes (Table 2). Hip, knee and ankle joint kinematics over the walking GC from the test and retest sessions are displayed in Fig. 2, with the associated SEM displayed in Fig. 3. At the hip the SEM was typically larger in the sagittal plane compared to the frontal and transverse planes over the walking GC (Fig. 3). SEM at the hip ranged from 2.9 to 4.1°, 2.7–3.7° and 1.9–3.9° in the sagittal, frontal and transverse planes. At the knee, the SEM was largest at initial contact and throughout terminal stance and the entire swing phase in the sagittal plane, and largest throughout mid-stance in the transverse plane. SEM values at the knee ranged from 1.6 to 4.2°, 1.0–1.9° and 1.3–2.9° in the sagittal, frontal and transverse planes, respectively. At the ankle, the SEM was largest over the entire GC in the transverse plane. SEM at the ankle ranged from 0.7 to 2.0°, 1.2–2.3° and 2.9–4.0° in the sagittal, frontal and transverse planes.

4. Discussion

There is need for a greater understanding of the reliability associated with 3DGA outputs in clinical populations [17], especially as the population assessed will inherently influence the reliability of the measurements [16]. Furthermore, with increasing moves towards waveform analysis within the biomechanics community the need to understand the reliability of the entire kinematic profile and not just variables at discrete time points becomes increasingly pertinent. This study quantified the test-retest reliability of lower limb kinematic waveforms over the walking GC within patients who had undergone THA. The findings of this study demonstrate that 3DGA provides a reliable means of quantifying lower limb kinematics over the entire walking GC in patients following THA, with the SEM below the 5° threshold previously suggested to identify clinically meaningful changes across all joints and in all planes [17]. That SEM values were below the clinically meaningful threshold is important, as error levels above 5° may result in misleading clinical interpretations about the efficacy or effect of interventions, such as THA. The SEM values reported provide researchers and clinicians with relevant thresholds which can be used to aid in the interpretation of data from 3DGA in patients following THA.

When exploring the SEM across joints, values are typically largest at the hip in the sagittal and frontal planes, and at the ankle in the transverse plane (Fig. 3). While the increased SEM at these joints in these planes may be due to variability in joint motion patterns, it is more likely the result of differences in marker placement between test and retest sessions. Difficulties locating pelvic landmarks, especially in participants with increased body fat or body mass index, as is evident within the THA population assessed, would potentially explain the increased SEM values at the hip. For instance, any differences in the height of the anterior superior iliac spine markers would result in changes in pelvic tilt and obliquity, resulting in altered sagittal and frontal plane hip kinematics. Differences in the anterior-posterior location of the metatarsal head markers would alter the magnitude of forefoot adduction or abduction reported about the ankle in the transverse plane. The suggestion that differences in marker placement between sessions is likely the cause of

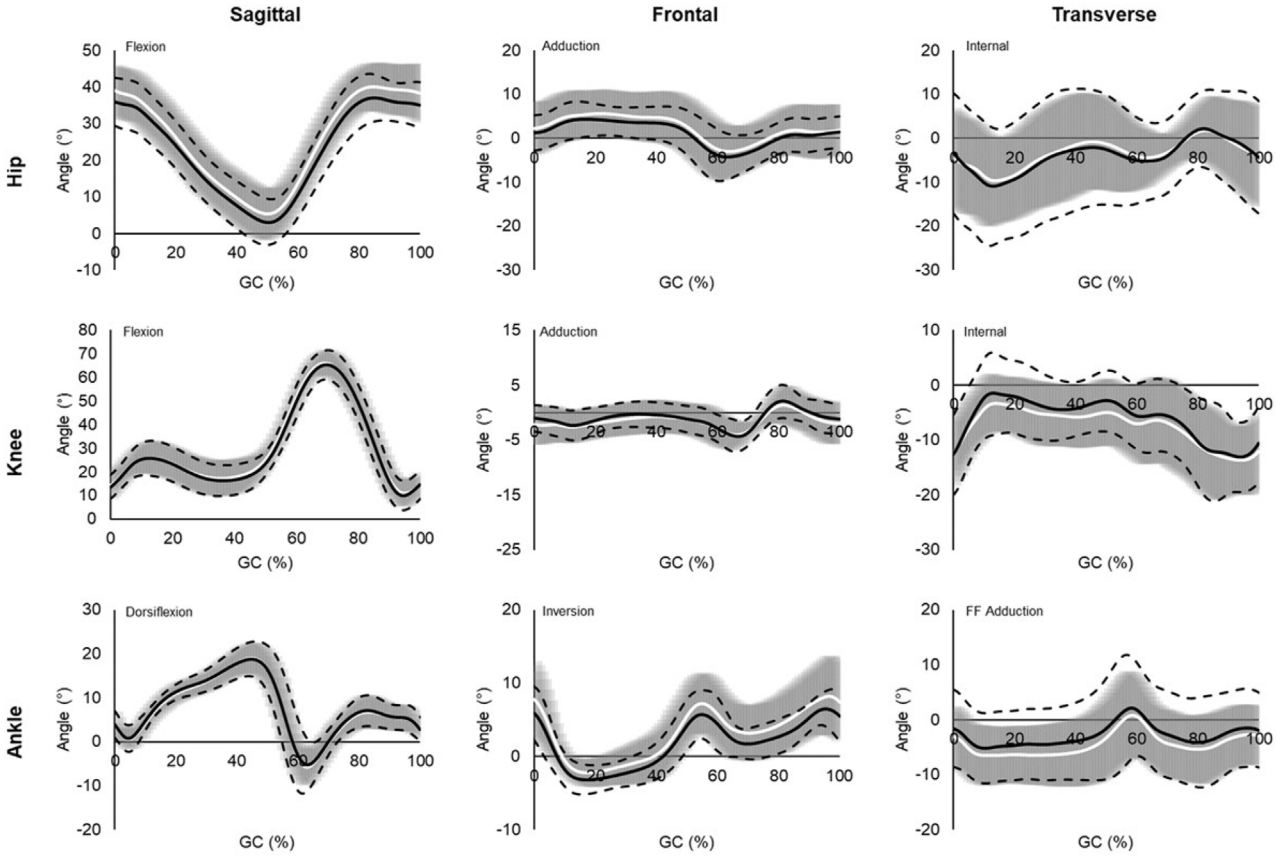

Fig. 2. Hip, knee and ankle joint kinematics in the sagittal, frontal and transverse planes over the walking gait cycle during test (mean = solid white line; SD = grey shaded region) and retest (mean = solid black line; SD = dashed black lines) sessions.

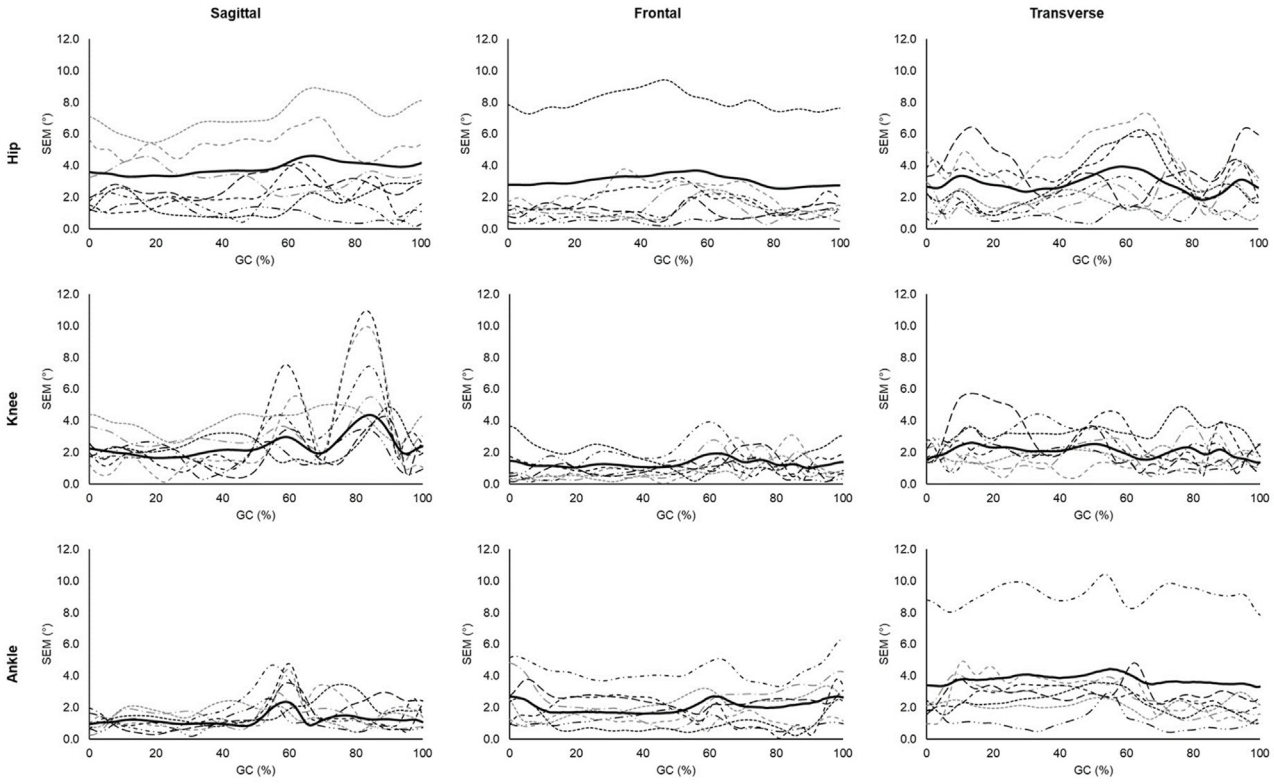

Fig. 3. Standard Error of the Measurement (SEM) associated with hip, knee and ankle joint kinematics in the sagittal, frontal and transverse planes over the walking gait cycle, for both individual patients (black or grey dotted or dashed lines) and the group (thicker solid black lines), respectively.

the increased SEM values for these joints, in these planes, is supported by the data in Fig. 2, which reveals relatively systematic and consistent shifts in movement patterns between test and retest sessions.

Exploring the deviation in the SEM over the kinematic waveforms, peaks are evident during terminal stance or early swing (50–70 % GC) for all joints in all planes, except for transverse plane knee kinematics (Fig. 3). These findings are likely indicative of increases in the variability of THA patients' movement patterns during terminal stance and early swing, which may be the result of altered dynamic stability [28]. Furthermore, these time periods within the GC are important, with THA patients displaying significant reductions in peak hip extension compared to healthy controls during terminal stance [3–6]. Additionally, while SEM values decrease at the hip and knee in the sagittal and frontal planes, and at the ankle in the frontal plane from initial contact through loading response (0–20 % GC), peaks within the SEM during loading response at the hip, knee and ankle are evident in the transverse plane (Fig. 2). These peaks occur around the instance of peak hip external rotation, knee internal rotation and forefoot abduction at the ankle (Fig. 2). As such the increased SEM at these time points may be indicative of alterations in either the timing or the magnitude of these peaks within the transverse plane.

The SEM reported for the THA population within this study is generally comparable in magnitude to that reported previously for younger healthy individuals using the same six-degrees of freedom model [21]. Interestingly though the pattern that emerges when comparing SEM values across planes differs between the THA and healthy populations. Typically, SEM values, or other reliability statistics, have been reported to be larger within the transverse plane during 3DGA within healthy populations [17,21]. In contrast, the SEM values reported within this study for patients following THA are of a similar magnitude across planes, with only transverse plane rotations at the ankle consistently displaying increased SEM. These findings are most likely due to differences in the participant populations, assessors, or a combination of these factors between studies.

Moving beyond the group level analysis and exploring individual SEM values reveals interindividual differences in patient specific SEM. On an individual level, SEM above the 5° clinically meaningful threshold were reported at the hip in the sagittal, frontal and transverse planes, at the knee in the sagittal and transverse planes, and at the ankle in the frontal and transverse planes (Fig. 3). It is apparent that the specific patient reporting SEM above 5° varies between planes and joints, with the factors identified previously, in paragraph 2 when exploring group level findings, likely explain the variation in SEM values between joints, planes and individual patients. While group level analysis is common within the literature [3–9], calculation of the SEM on an individual level could be used to identify patient specific thresholds to detect true subject specific responses to different interventions designed to enhance lower limb kinematics in patients following THR.

The small sample size associated with this work is the primary limitation of this study. Unfortunately, due to staff turn-over, the small sample size was unavoidable, especially as the authors wished to remove additional sources of variability (numerous assessors) associated with 3DGA from the data set. While the sample size is small, it is comparable to those utilised in previous studies [11,21] reporting on the reliability of 3DGA in healthy populations. The time of the assessment was set at 12 months post-operatively or beyond due to the changes in joint kinematics reported throughout the first post-operative year [7–9,29]. Further work is required to explore the reliability of 3DGA in patients who have undergone THA throughout the first post-operative year to aid in the interpretation of changes reported in lower limb kinematics throughout this period. Finally, previous work [21] has revealed that SEM values differ between different biomechanical models and as such the findings of the study may only be applicable to similar six degrees-of-freedom models.

5. Conclusion

This study quantified the test-retest reliability of lower limb kinematic waveforms over the walking GC in patients following THA. The

findings demonstrate that 3DGA provides a reliable means of quantifying lower limb kinematics in patients following THA, with the SEM below the 5° threshold previously suggested to identify clinically meaningful changes, across all joints and in all planes. The SEM values reported can be utilised to aid the interpretation of data generated using 3DGA in patients following THA, ensuring that small changes are not over emphasised within either applied or research settings.

Author contributions

BL, CW and TB conceived the study. HG undertook data collection. BL undertook data analysis. All authors aided in the design of the study, data interpretation, drafting of the manuscript and approved the final version of the manuscript.

Conflict of interest

TB receives royalties, consulting fees and/or payment for lectures and presentations from DePuy Synthes, Symbios and Eventum Orthopaedics. The other authors declare no competing interests.

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