Validation of an electrogoniometry system as a measure of knee kinematics during activities of daily living

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Running title: Validation of electrogoniometry

Purpose: The increasing use of electrogoniometry (ELG) in clinical research requires the validation of different instrumentation. The purpose of this investigation was to examine the concurrent validity of an ELG system during activities of daily living.

Methods: Ten asymptomatic participants gave informed consent to participate. A Biometrics SG150 electrogoniometer was directly compared to a 12 camera three dimensional motion analysis system during walking, stair ascent, stair descent, sit to stand, and stand to sit activities for the measurement of the right knee angle. Analysis of validity was undertaken by linear regression. Standard error of estimate (SEE), standardised SEE (SSEE), and Pearson's correlation coefficient *r* were computed for paired trials between systems for each functional activity.

Results: The 95% confidence interval of SEE was reasonable between systems across walking (LCI = 2.43 °; UCI = 2.91 °), stair ascent (LCI = 2.09 °; UCI = 2.42 °), stair descent (LCI = 1.79 °; UCI = 2.10 °), sit to stand (LCI = 1.22 °; UCI = 1.41 °), and stand to sit (LCI = 1.17 °; UCI = 1.34 °). Pearson's correlation coefficient *r* across walking (LCI = 0.983; UCI = 0.990), stair ascent (LCI = 0.995; UCI = 0.997), stair descent (LCI = 0.995; UCI = 0.997), sit to stand (LCI = 0.998; UCI = 0.999), and stand to sit (LCI = 0.996; UCI = 0.997) was indicative of a strong linear relationship between systems.

Conclusion: ELG is a valid method of measuring the knee angle during activities representative of daily living. The range is within that suggested to be acceptable for the clinical evaluation of patients with musculoskeletal conditions.

Key words: validation, electrogoniometry, knee.

Introduction

Sagittal knee angles have been traditionally measured in non-weight bearing activities, during both supine lying and sitting conditions using manual goniometry (1). It has been suggested that these methods are dissimilar to sagittal knee kinematics during functional activity (2). The use of electrogoniometry in the monitoring of sagittal knee kinematics can provide an opportunity to measure everyday functional activities (3-5). This can be undertaken in controlled laboratory environments (3-5), or away from laboratory observation (6).

The measurement of the sagittal knee angle using manual goniometry is reliant upon the identification of the centre of joint rotation (7). This becomes increasingly difficult during displacement, as the knee translates in both medio-lateral and antero-posterior directions (8). Three dimensional motion analysis systems can accurately estimate the centre of knee joint rotation (9), however, they require a fixed laboratory based camera system (4), and therefore cannot measure patients outside of a restricted laboratory area. Electrogoniometry systems provide continuous measurement of sagittal knee motion, whilst measuring the angle between two axes defined by the two extremities of the transducer. At the knee joint, the angle is measured between the femoral and tibial segments, rather than relying on the identification of the centre of knee joint rotation (5).

Electrogoniometry is being increasingly used to assess clinical populations (5, 10-14). As such, there is a requirement to ascertain the validity of different systems (3). Electrogoniometry has been previously shown to be a valid measure of knee kinematics (1). Different electrogoniometers and data acquisition systems are frequently used in electrogoniometry, therefore, generalisation of the findings due to electronic component differences across instrumentation cannot be reliably undertaken (15). Piriyaprasarth et al. (9)

assessed the reliability of knee joint position using the Biometrics SG150 electrogoniometer. The validity, however, was assessed against a Perspex template using a static protocol, deriving errors of 0.8 ° to 3.6 ° over an angular range of 0 ° to 90 °. Maupas et al. (16) assessed the validity of the Biometrics SG150 electrogoniometer when attached to a mechanical goniometer, as part of a wider assessment of validity during asymmetric leg activity. The authors reported a mean difference of 1.3 ° ±1.1 ° (range = 0 ° - 4 °) when the mechanical goniometer was moved through the range of -160 ° to +160 ° measured at ten degree increments.

Validation of the Biometrics SG150 electrogoniometer has also been undertaken in humans, with Rowe et al. (1) reporting mean differences of 1.5 ° ±2.8 ° during walking when compared to a three dimensional motion analysis system. This range was suggested by the authors to be acceptable for the clinical evaluation of patients with musculoskeletal disorders (1). Bronner et al. (17) determined the validity of the Biometrics SG150 electrogoniometer across various dancing movements, obtaining validity correlations of $r \geq 0.949$ (SEM ≤ 6.80 °) to three dimensional motion analysis at the knee joint.

To the best of our knowledge, no studies have assessed the validity of the Biometrics SG150 device in humans across a range of activities representative of those undertaken during daily living. The objective of this study was to determine the concurrent validity of the Biometrics SG150 electrogoniometer by comparing sagittal knee angular displacements to a three dimensional motion analysis system, referred to as the "gold standard" of knee kinematic monitoring (1), during walking, stair ascent, stair descent, sit to stand, and stand to sit activities. Electrogoniometry has the potential to be used in regular clinical assessments, and

is routinely used for research applications. This investigation was undertaken to derive error confidence intervals to scientifically inform practitioners of the validity of a typical electrogoniometer during common ambulatory activities of daily living, in addition to providing reference values to aid data interpretation.

Method

Participants

Ethical approval for the study was granted by the institutional ethics committee. Ten asymptomatic male participants were recruited and gave written informed consent prior to participation. Participants had a mean age of 23.1 ±3.69 yrs, height of 1.79 ±0.07 m, mass of 81.57 ±7.79 kg, and body mass index (BMI) of 25.42 ±2.21 kg/m^2. Exclusion criteria were current lower extremity injuries that could prevent or restrict the performance of repeated walking, stair ascent, stair descent, sit to stand, and stand to sit movements. Due to the accuracy required for validation purposes, participants were excluded if they had a BMI ≥ 30.00 kg/m^2.

System preparation

Electrogoniometry system

A twin axis electrogoniometer (SG150, Biometrics, Gwent, UK) was used in the experiment. The electrogoniometer was attached to a portable data logger (8 channel data logger, MIE Medical Research, Leeds, UK) via a preamplifier (MIE Medical Research, Leeds, UK). A sampling frequency of 200 Hz was used to ensure consistency with the motion analysis system, as well as previous research using electrogoniometry (9, 18, 19).

Two electronic foot switches (MIE Medical Research, Leeds, UK) were used in the electrogoniometry system as a method of identifying heel strike and toe off events, in addition to enabling synchronisation with the motion analysis system. Foot switches were used for level walking, stair ascent, and stair descent in which heel strike and toe off events occurred. Sit to stand and stand to sit trials began with the participant balancing on the contralateral leg with the ipsilateral leg held above the force plate, and then placing the ipsilateral leg in contact with the force plate to enable synchronisation.

During electrogoniometer attachment, participants were asked to stand in the anatomical position, with the knees in full extension. The anatomical line was marked between the greater trochanter of the femur and the lateral epicondyle. The same protocol was undertaken for the shank, with the line between the lateral epicondyle and the lateral malleolus identified and marked (Figure 1). Double sided hypoallergenic tape was used to attach the endplates to the skin. Microporous surgical tape was applied perpendicular to the endplates to secure attachment.

The live data preview function in MyoDat (6.59.0.8260, MIE Medical Research, Leeds, UK), the instrumentation set-up and analysis software for the data logger, was used to observe the real time output of the electrogoniometer and foot switches. Each participant was asked to flex and extend their knee throughout their full range of motion (ROM), as well as placing their ipsilateral forefoot and heel in contact with the ground to verify correct operating function of both instruments.

Three dimensional motion analysis system

A 12 camera three dimensional motion analysis system (Vicon MX, Oxford, UK) was calibrated through a standard dynamic protocol using a five marker calibration wand (Vicon, Oxford, UK). The calibration was accepted when all 12 cameras (T20, Vicon, Oxford, UK) exhibited an image error of < 0.2 mm. Participants had their height and mass taken, along with bilateral leg length, and knee and ankle widths in order to fit the participant's specific dimensions to the lower body 'Plug in Gait' model (Vicon, Oxford, UK). Fourteen retroflective markers (Ø = 14 mm) were placed bilaterally over anatomical landmarks on the lower body in line with the recommendations of the system manufacturer. These locations were the anterior superior iliac spine, posterior superior iliac spine, lateral distal third of the thigh, lateral distal third of the shank, lateral malleolus, heel on the calcaneous, and the head of the second metatarsal. Kinematic data were subsequently captured at 200 Hz into Vicon Nexus (1.7.1, Vicon, Oxford, UK).

Four force plates (OR6-7, AMTI, Watertown MA, USA) were embedded within a 7 m walkway in the centre of the calibrated volume. Four amplifiers (MiniAmp MSA-6, AMTI, Watertown MA, USA) were used to amplify the signal into Nexus at a gain of 1000, with kinetic data captured at 1000 Hz.

The experimental set-up of the retroflective markers and the components of the electrogoniometry system prior to static calibration in the motion analysis system are depicted in Figure 1. Two knee alignment devices ((KADs) Vicon, Oxford, UK)) were then placed bilaterally over the medial and lateral epicondyles to independently define the

alignment of the knee flexion/extension axis. Following data capture of a static trial, the KADs were removed and two retroflective markers (Ø = 14 mm) were placed bilaterally over the lateral epicondyles of the knee.

Protocol

The participants undertook a number of walking trials until three were collected in which the right foot made contact with a force plate during both heel strike and toe off events. Three stair ascent trials starting with the right foot were then performed on a custom built stair rig constituting three steps (width = 630 mm; tread = 270 mm; height = 200 mm), with the first step being a force plate (MC818, AMTI, Watertown MA, USA). Whilst standing at the top of the stair rig, participants then undertook three stair descent trials starting with the right foot such that their right foot landed on the force plate. Three sit to stand trials from an orthopaedic stool (Nottingham Rehab Supplies, Nottingham, UK) were then performed, with the stool kept at a consistent height of 560 mm. During the sit to stand movement, participants were instructed to cross their arms, so that the upper arm was parallel to the floor in the sagittal plane to avoid marker occlusion. Three stand to sit trials were then performed.

Data analysis

Three dimensional motion analysis system

Right heel strike and toe off events in walking and stair ascent were determined by the vertical component of the ground reaction force (vGRF). Marker trajectories in x, y, and z axes were used to identify the initial heel strikes and toe offs in stair descent due to the fixed position of the step force plate at the bottom of the stair rig. Sit to stand and stand to sit trials were also determined by the onset of the vGRF in the ipsilateral leg.

Trials were processed in Vicon Nexus by filling marker trajectory gaps in the data using a Woltring quintic spline routine when the gaps were < 10 frames (20). Longer gaps were filled using a pattern fill function, adopting the trajectory of a marker with a similar displacement trail. Marker trajectories and kinetic data were filtered using a fourth order low pass Butterworth filter with zero lag. A cut off frequency of 6 Hz and 300 Hz was used for marker trajectories and kinetic data, respectively. The dynamic gait model was subsequently applied to retrieve the right sagittal knee angular displacement trace.

Electrogoniometry system

Data from the electrogoniometry system were uploaded into MyoDat and exported into Microsoft Excel (Microsoft, Redmond, WA, USA) where they were identified from the relating foot switch output. The trials were then imported into MATLAB (R2007b, MathsWorks, Natick, MA, USA) and were filtered using a low pass finite impulse response filter.

Combined

An analysis of validity by linear regression was undertaken using a spreadsheet developed by Hopkins (21). The standard error of estimate (SEE), the magnitude of error expressed as a standard deviation between systems, was derived from the analysis spreadsheet. This parameter has been suggested for use in validity studies (22), and has been used previously as an indicator of error in a validation assessment (23). Standardisation was undertaken by dividing the SEE by the standard deviation of the motion analysis data set to obtain the standardised SEE (SSEE). The SSEE was interpreted using a modified Cohen scale (24).

Predicted residual sums of squares (PRESS statistic) was used to calculate the new prediction error of a potential participant drawn randomly from the same population. Pearson's correlation coefficient *r* was derived to depict the linear relationship between the electrogoniometer and motion analysis system throughout the displacement cycles of walking, stair ascent, stair descent, sit to stand, and stand to sit. Data were input into the linear regression analysis for both systems in raw format sampled at 200Hz, with no extrapolation undertaken. Specific gait and movement cycles were the same numerical length for both systems within trials.

Results

A representative example of the initial raw data excursion, prior to linear regression, is presented in Figure 2. Walking produced a Pearson's correlation coefficient *r* of 0.987 (LCI = 0.983; UCI = 0.990), which was the weakest relationship amongst the five activities. Stair ascent (LCI = 0.995; UCI = 0.997), stair descent (LCI = 0.995; UCI = 0.997), sit to stand (LCI = 0.998; UCI = 0.999), and stand to sit (LCI = 0.996; UCI = 0.996) all produced correlations of > 0.995 (Table 1).

Level walking produced the greatest SEE (2.65 °; LCI = 2.43 °; UCI = 2.91 °) across the five activities, although the magnitude of the SSEE was described as 'trivial' (0.15; LCI = 0.14; UCI = 0.17) (Table 2). The smallest SEE was observed in the stand to sit movement (1.25 °; LCI = 1.17 °; UCI = 1.34 °), with the displacement producing a SSEE interpreted as 'trivial' (0.07; LCI = 0.07; UCI = 0.08). Stair ascent produced a greater error (2.24 °; LCI = 2.09 °; UCI = 2.42 °) than that of stair descent (1.93 °; LCI = 1.79 °; UCI = 2.10°), with sit to stand similar to that of stand to sit (1.30 °; LCI = 1.22 °; UCI = 1.41 °). The predicted residual sums of squares (PRESS) error was subsequently greatest in level walking (2.66 °), and smallest in

stand to sit (1.25 °). If a participant was drawn randomly from the same population, the linear regression model can be generalised to derive a SEE of 1.88 ° between the electrogoniometer and motion analysis system across the five activities examined.

Discussion

The aim of this study was to determine the concurrent validity of the Biometrics SG150 electrogoniometer during activities of daily living in order to present error confidence intervals for practitioners using the instrumentation. The device was compared to three dimensional motion analysis, a technique deemed accurate (25), and when applied, capable of measuring knee biomechanics to a high degree of precision (26). In addition, motion analysis has been described as the "gold standard" for knee kinematic measurement during previous electrogoniometry validation (1).

The SEE, which was the magnitude by which the electrogoniometer output differed from the motion analysis system output for any given participant over an activity displacement cycle, was found to range from 1.25 ° during stand to sit to 2.65 ° in walking. The 95 % confidence interval of the SEE was found to be greatest in walking (2.43 ° – 2.91 °), and subsequently lowest during stand to sit (1.17 °– 1.34 °). Measurement error can arise from a combination of the electrogoniometer, the researcher, or the participant who is being measured (27). The magnitude of error in this investigation coincides with that of previous studies (1, 19), with Rowe et al. (1) presenting differences of 1.5 ° ±2.8 ° during walking. In the current investigation, the upper 95 % confidence error limit of walking was within the range suggested by Rowe et al. (1) to be valid for clinical use. In an effort to reduce the measurement error, Rowe et al. (1) mounted the endplates of the electrogoniometer upon plastic strips, with a view to reducing skin motion artefacts by avoiding direct instrument to

skin contact. Foam blocks were also used to reduce the abduction and adduction angulation at the knee in order to attach the instrument in a straight configuration. In the current investigation, mounting of the electrogoniometer directly onto the skin was undertaken with a view to examining the validity of an attachment procedure that could be used with increased time efficiency and a reduced degree of difficulty, as recommended by the manufacturer, and also more suited to applied use. It is perhaps surprising, therefore, that a greater magnitude of error was not established in the current investigation due to the methodological differences compared to Rowe et al. (1). Indramohan et al. (3), however, also found that their results were unaffected when attaching the electrogoniometer directly onto the skin in a study validating a data logger for use with electrogoniometers. These findings suggest that accurate data can be obtained when the electrogoniometer is attached directly onto the skin, although a meticulous protocol must be followed to minimise error. This provides support for the use of the attachment procedure described in the current investigation in applied settings where preparation time is often limited. The results of current investigation and Rowe et al. (1) suggest that reasonable errors are derived when using electrogoniometry, regardless of attachment procedure.

The mean linear relationship between the electrogoniometer and motion analysis system was found to be very high across walking, stair ascent, stair descent, sit to stand, and stand to sit activities, ranging from 0.987 in walking to 0.998 during sit to stand. These findings were similar to a previous validation report by Bronner et al. (17) who described correlations of ≥ 0.949 between an electrogoniometer and motion analysis system when measuring the sagittal knee angle. A similar magnitude of Pearson's correlation coefficient *r* was observed, although Bronner et al. (17) found a slightly reduced magnitude than that presented in the current investigation. A potential explanation for this difference is that ten dancing

movements were assessed in advanced level collegiate dancers. Dancing movements are often performed at joint extremes (17), and therefore likely to assume greater magnitudes of displacement and velocity than those seen during walking, stair ascent, stair descent, sit to stand, and stand to sit displacements. Electrogoniometry has been found to display reduced accuracy at motion extremes at the wrist (28), knee (1), and during laboratory investigation (15).

A potential limitation of the current investigation is the effect of soft tissue artefact inaccuracies often associated with three dimensional motion analyses (29, 30). These errors originate from movement or deformation of the subcutaneous tissues associated with muscular contractions, skin movement and inertial effects (31). To reduce the effect of soft tissue artefact errors, participants were excluded if they had a body mass index of ≥ 30 kg/m^2. It was hypothesised that participants classified as obese, from the guidelines reported by the World Health Organisation (32), would have an increased subcutaneous tissue layer and therefore be susceptible to greater skin translation during displacement. In the current investigation, retroflective markers were attached to bony anatomical landmarks, where typically, the thickness of the subcutaneous layer is considerably reduced. This, coupled with the exclusion criteria at the investigation outset, suggests that the measured angular displacements were likely to reflect true knee movement across walking, stair ascent, stair descent, sit to stand, and stand to sit activities. A further limitation is that only young male participants were studied. Care must be taken, therefore, when generalising the results to other populations, in particular, older symptomatic populations that may be indicative of greater ambulatory variability.

It can be concluded that the Biometrics SG150 electrogoniometer displays errors that are deemed acceptable for the clinical evaluation of patients with musculoskeletal disorders. The instrument is valid when measuring sagittal knee angular displacements during walking, stair ascent, stair descent, sit to stand, and stand to sit activities of daily living. Due to the increasing clinical regard for electrogoniometry, future work should assess the validity of specific symptomatic populations to optimise the scientific rigor of clinical decisions in order to provide the best evidence based patient care.

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Table 1 – Pearson's correlation coefficient *r* depicting the linear relationship between the electrogoniometer and the motion analysis system during walking, stair ascent, stair descent, sit to stand, and stand to sit activities across ten participants

	Pearson's correlation coefficient *r*	95% confidence interval	
Walking	0.987	0.983	0.990
Stair ascent	0.996	0.995	0.997
Stair descent	0.996	0.995	0.997
Sit to stand	0.998	0.998	0.999
Stand to sit	0.997	0.996	0.997

Table 2 – Standard error of estimate (SEE) and standardised SEE (SSEE) between the electrogoniometer and the motion analysis system during walking, stair ascent, stair descent, sit to stand, and stand to sit activities across ten participants. A modified Cohen scale gives interpretation of the magnitude of the standardised error. < 0.2 = trivial; 0.2 - 0.6 = small; 0.6 - 1.2 = moderate; 1.2 - 2 = large; > 2 = very large (24)

	SEE (°)	95% confidence interval (°)		SSEE	95% confidence interval (°)		Modified Cohen's *d*	PRESS error (°)
Walking	2.65	2.43	2.91	0.15	0.14	0.17	Trivial	2.66
Stair ascent	2.24	2.09	2.42	0.08	0.08	0.09	Trivial	2.25
Stair descent	1.93	1.79	2.10	0.08	0.08	0.09	Trivial	1.94
Sit to stand	1.30	1.22	1.41	0.06	0.05	0.06	Trivial	1.31
Stand to sit	1.25	1.17	1.34	0.07	0.07	0.08	Trivial	1.25

Figure 1 – Set-up of the retroflective markers and the components of the electrogoniometry system on a participant before static calibration in the motion analysis system. At this point, markers were not placed on the knee. Lines denote the anatomical lines of the femur and shank. GT = greater trochanter; LE = lateral epicondyle; LM = lateral malleolus.

Figure 2 – Representative trace of the right sagittal knee angular displacement as the initial output of the electrogoniometry (−) and motion analysis (- -) systems in one participant across one trial in level walking (I), stair ascent (II), stair descent (III), sit to stand (IV), and stand to sit (V).

Figure 1

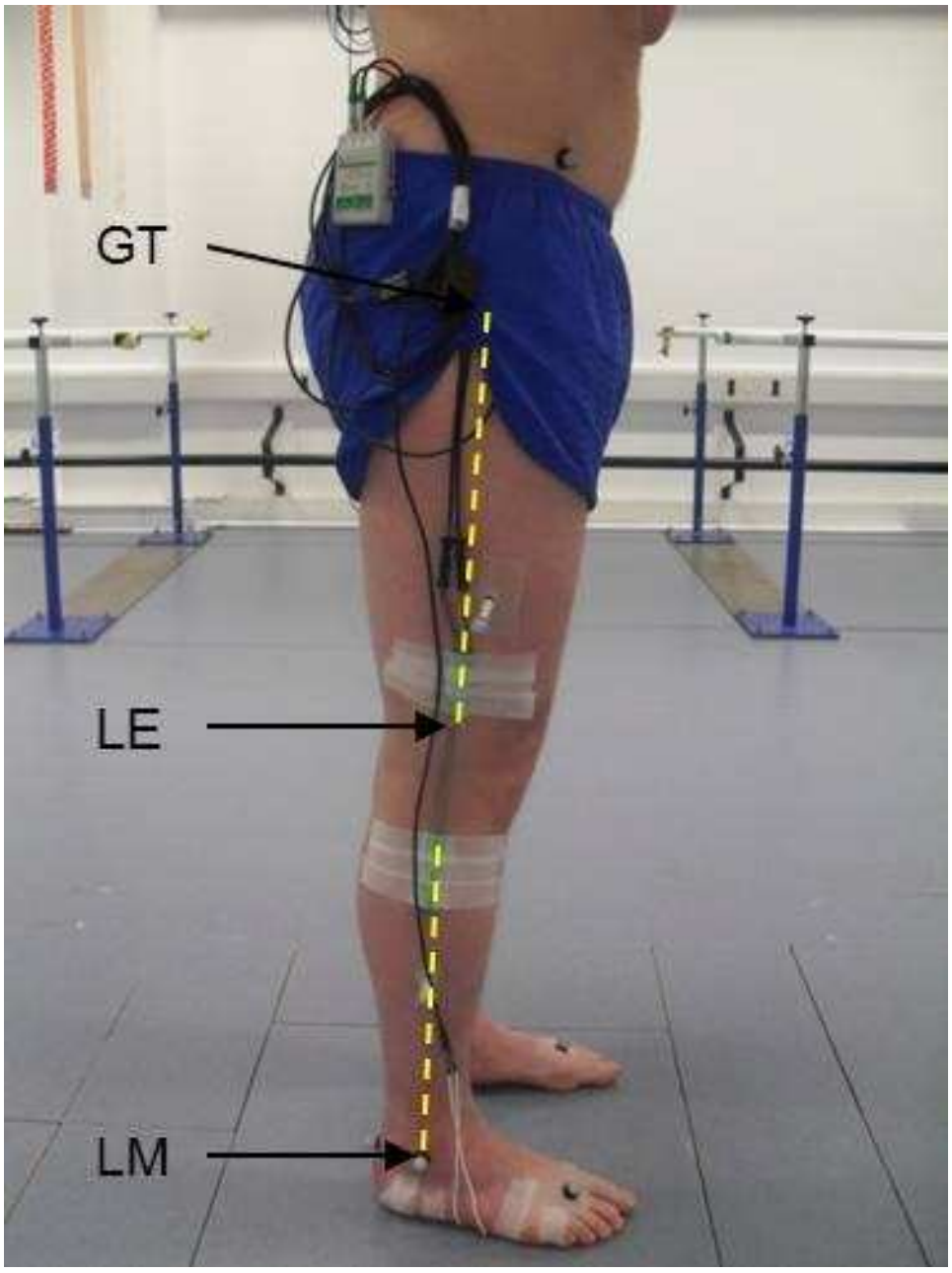
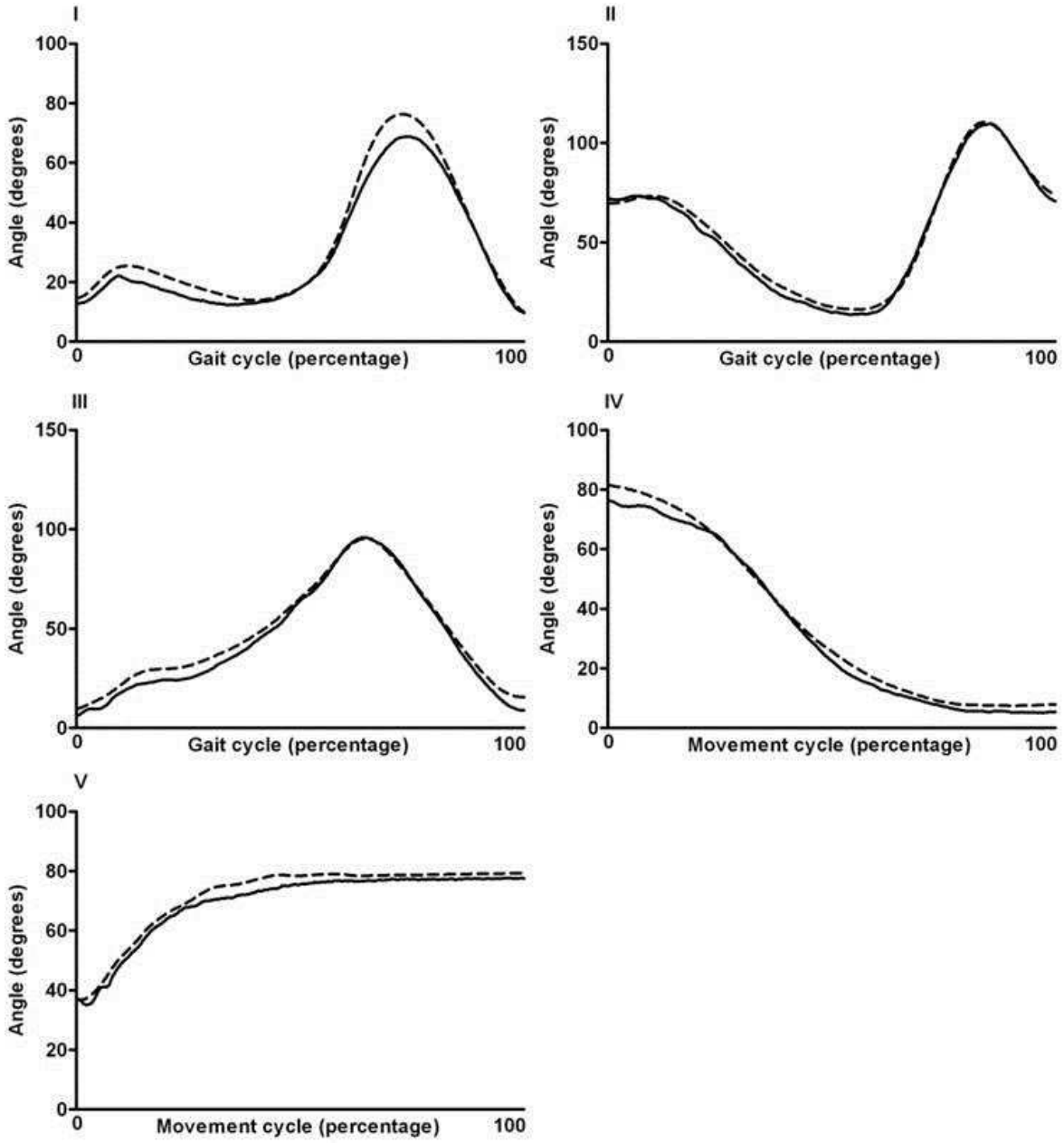


Figure 2


I
Angle (degrees)
100
80
60
40
20
0
0
Gait cycle (percentage)
100
II
Angle (degrees)
150
100
50
0
0
Gait cycle (percentage)
100
III
Angle (degrees)
150
100
50
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0
Gait cycle (percentage)
100
IV
Angle (degrees)
100
80
60
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20
0
0
Movement cycle (percentage)
100
V
Angle (degrees)
100
80
60
40
20
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Movement cycle (percentage)
100