Routine Clinical Motion Analysis: Comparison of a Bespoke Real-Time Protocol to Current Clinical Methods

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Abstract

Motion analysis (MA) hardware has recently become more accessible; however, protocols have not developed in conjunction. Routine clinical assessment mostly relies on unreliable observational methods. This study aimed to develop an MA protocol for routine clinical use and compare kinematics and reliability to the gold-standard. Ten participants completed 10 over ground walks with a comprehensive marker set (bespoke and gold-standard). Inter/intra-assessor reliability was also compared. Results demonstrated comparable kinematics. Reliability of the bespoke model was lower than the gold standard but higher than observational methods. The bespoke model can be recommended for routine clinical use to assess patient progress and function.

Keywords: motion analysis; gait; kinematics; reliability

Introduction

Three dimensional motion analysis is the current 'gold standard' for measuring human movement (Gage 1993; Cook et al. 2003). A motion analysis protocol can be defined as the process required to extract useful information from a motion analysis session (Ferrari et al. 2008). To date, a number of protocols have been well established and validated for use in complex clinical cases and research. Recently, motion capture hardware has become more advanced and more accessible, potentially expanding its use beyond research and complex clinical cases into routine clinical assessment (Carse et al. 2013). However, current use of motion analysis in a routine clinical setting is still limited due to complex and time consuming protocols (Toro et al. 2003). The majority of motion capture laboratories continue to use original protocols and any variations remain restricted to research environments. Furthermore, current protocols rarely allow for real-time measurement; a crucial component of routine clinical assessment, where quick and accurate information about patient function is required.

Current routine clinical methods for assessing patient function are mostly carried out using observational methods (Carse et al. 2013). A number of clinically validated observational scores are available which allow classification of gait for patients with pathological movement patterns (Palisano et al. 1997; Read et al. 2003). However, evidence suggests that these methods may not be the most accurate or sensitive way to assess patient progress or measure functional outcome (Kawamura et al. 2007; Ong et al. 2008; Williams et al. 2009). Further, the majority of observational scoring methods have been developed specifically for measurement of gait and therefore are not appropriate for quantifying functional movement or range of motion (ROM) during other activities of daily living. A number of clinicians use manual goniometers to measure active and passive joint ROM using static, end of range poses. While this method is more accurate than observational techniques, there is still significant variability when compared to instrumented measurement methods (Nussbaumer et al. 2010), and furthermore, manual goniometers cannot be used to measure dynamic functional movements.

Therefore, there exists both the potential and the need for three dimensional movement analysis in routine clinical assessment. However, in order to achieve this, protocols must be adjusted to suit the needs of a routine clinical environment. The most widely used protocol (Vicon Plug in Gait; PiG; Oxford Metrics Ltd., UK) employs a number of individual skin surface markers which require substantial training and experience to apply correctly. As an alternative, a number of authors have suggested the use of rigid clusters of markers (Cappozzo 1991; Manal et al. 2000), as these are quicker and easier to apply and also allow for different methods of patient calibration; such as functional methods or a digitiser.

Few studies have investigated the effects on kinematic output between cluster based protocols and individual marker protocols. However, one study has suggested that the kinematic output is comparable (Collins et al. 2009).

While cluster based protocols may offer several advantages over single marker protocols, currently available cluster based solutions are still unlikely to be suitable for routine clinical use as they may still require extensive technical expertise to administer and analyse.

Therefore, the aim of this study was to develop a cluster based motion analysis protocol for routine clinical use, capable of delivering 3D kinematics in real-time and also to compare the kinematic output and data reliability to the current clinical motion analysis methods.

Materials and Methods

Figure 1 shows the cluster marker set which was developed for this study (Strathclyde Cluster Model; SCM). Anatomical landmarks (ALs) for calibration (figure 2) are located using a digitiser (a cluster mounted on a pointer).

[figure 1]

The positions of ALs are stored using the cluster local coordinate system, allowing 'virtual' markers to be recreated from the moving cluster in real-time. Clusters were tracked using Vicon Nexus (v2.2.3; Oxford Metrics Ltd.,U.K) software and marker positions were streamed into an object orientated movement analysis application development package (D-Flow v3.18; Motekforce Link, Netherlands).

[figure 2]

Once 'virtual' anatomical points had been recreated, all anatomical reference frames were calculated in accordance with the International Society of Biomechanics recommendations (table 1; Grood & Suntay 1983; Wu et al. 2002) and kinematics were calculated using the Grood and Suntay/Cole methods (Grood & Suntay 1983; Cole et al. 1993).

[table 1]

One advantage of this method over current clinical methods is that once the patient has been calibrated, kinematics are calculated and displayed in real-time (figure 3). This allows the

patient to receive immediate feedback on their movement. It may also allow clinicians to make quick, informed, decisions about the best course of treatment or therapy.

[figure 3]

This study was approved by the ethics committee of the Department of Biomedical Engineering, University of Strathclyde, Glasgow, UK and all participants provided informed consent to take part. Comparison and reliability investigations were carried out for SCM compared to PiG.

Comparison of Kinematic Output

Ten participants (four males, mean age, 25 ± 3) volunteered to take part and were assessed by one assessor. All participants were able bodied, had normal lower limb function and were able to walk at a self-determined pace for approximately 500m without excess physical exertion or pain. A comprehensive marker set allowed participants to wear both PiG and SCM simultaneously (figure 2). For ease of calibration when using a comprehensive marker set, skin surface markers were used to identify ALs for SCM. There was some overlap between PiG markers and SCM calibration markers, in which case, these markers were used for both protocols. Medial markers were placed on the femoral epicondyles and tibial malleoli for static calibration capture only and were removed for dynamic trials. Single markers were attached by the same assessor for all participants using double sided hypo-allergenic tape.

For each participant, a minimum of 10, shod, over ground walking trials were captured at 100Hz over a 10m long walkway at a self-selected pace. Data were captured using a 12 camera Vicon T-Series motion capture system (Vicon MX Giganet, Oxford Metrics Ltd., UK). Trial data for each protocol were processed using the respective methods required for each marker set. PiG data were processed using the standard dynamic PiG pipeline in Nexus

2.2.3. SCM data were processed in D-Flow using bespoke code. All marker trajectories were filtered with a 4th order Butterworth filter with a cut of frequency of 10Hz. Data reduction and analysis were performed using MATLAB (Mathworks Inc). Comparisons were made between pelvic tilt, obliquity and rotation and also for flexion/extension, abduction/adduction and internal/external rotation for the right and left hip and knee. Right and left ankle dorsi/plantar flexion was also compared. Further, the total excursion of the pelvis and each joint as measured by each model was compared along with a number of typical kinematic parameters (H1 – peak hip extension, H2 – peak hip adduction in stance, K1 – peak knee flexion in loading response, K2 – peak knee flexion in swing, K3 – peak knee abduction in swing, A1 – peak ankle dorsiflexion and A2 – peak ankle plantarflexion).

Reliability

One able bodied participant (age: 22, mass: 62kg, height: 180cm) and five assessors of varying levels of experience in gait analysis volunteered to take part in a second part of the study. All assessors attended a familiarisation session where procedures and marker placement for each model were outlined. In order to minimise inter session variability, the same participant was used for all sessions and the same clothing and shoes were worn. Each assessor applied the comprehensive marker set once over a two-week period. In this instance, digitiser calibration was used for SCM, in order to also assess the reliability of different calibration methods. Two assessors (assessor two and assessor three) applied both markers sets on three occasions within a two-week period. Walking trials were performed on a treadmill which was set at a fixed speed of 1.18 m/s. A two-minute familiarisation period was followed by 30 seconds of data capture. Marker trajectories were captured using the same motion capture system described above and data were processed using methods for each respective model, as above. Standard deviation (SD) and Intraclass Correlation Coefficient (ICC) were used to compare inter and intra-assessor variability and reliability.

Results

Comparison

Similar trends were seen for right and left legs, therefore only data from the right leg is presented. Figure 4 shows mean kinematics ± 2 SD for PiG and SCM outputs for all participants. Overall, agreement was good between the protocols.

[figure 4]

Pelvic tilt and ankle dorsi/plantarflexion resulted in the best agreement. Worst agreement was observed in hip and knee int/ext rotation. For the hip, SCM estimated greater extension and adduction in stance than PiG and there was little agreement between protocols for hip int/ext rotation. For the knee both protocols estimated similar flexion in stance; however, SCM overestimated flexion and underestimated abduction in swing when compared to PiG. Again, there was little agreement between protocols for knee int/ext rotation. For ankle dorsi/plantarflexion, results demonstrated very similar outputs during stance; however, SCM estimated slightly higher dorsiflexion in swing in comparison to PiG. Table 2 details joint excursion for each model and comparisons between kinematic values at specific stages of the gait cycle.

[table 2]

For the pelvis, PiG estimated lower excursions than SCM for all rotations, resulting in a significant difference for tilt, obliquity and rotation. There were significant differences between protocols for all hip excursions and also H2 (P <0.001, $\alpha = 0.05$). There were significant differences in all knee excursions. There were also significant differences between protocols for all knee parameters. Best agreement between protocols was observed for the ankle as there were no significant differences between dorsi/plantarflexion excursion ($P = 0.386$, $\alpha = 0.05$) A1 ($P = 0.488$, $\alpha = 0.05$) or A2 ($P = 0.792$, $\alpha = 0.05$) between

protocols. Despite the number of significant differences, aside from internal/external rotation data, the average difference in protocols was 3.9° for the parameters calculated.

Reliability

Inter/intra assessor reliability results are detailed in table 3. Inter assessor SD values were similar for PiG and SCM. The largest difference was observed in knee internal/external rotation. ICC values were good for all PiG outputs except pelvic tilt. SCM also resulted in good ICC values for most parameters, except pelvic tilt and hip internal/external rotation.

Intra assessor results for two assessors are also shown in table 3. ICC values for assessor two were similar for PiG and SCM, except for pelvic obliquity (0.97 and 0.04 for PiG and SCM, respectively). Assessor three demonstrated higher ICC values for all pelvic parameters when using PiG compared to SCM. However, for the knee, assessor three demonstrated higher ICC values with SCM compared to PiG.

[table 3]

Discussion

The bespoke protocol used in this study (SCM) was developed specifically for routine clinical use. The cluster markers used were designed to be quick and easy to apply and once the participant has been calibrated, kinematics are measured and displayed in real-time. This is an advantage over current protocols for routine clinical assessment as results can be obtained immediately, without the need for offline processing and analysis and hence can be used for immediate feedback to the patient and their care team. The aim of this study was to compare the kinematic output and reliability of SCM to the current clinical gold-standard. For kinematic output, good agreement was observed in the sagittal plane for all joints; however, movements in the other planes highlighted some differences between protocols. For the knee, PiG estimated lower flexion and higher abduction in swing than SCM. PiG measured up to 30° of abduction which is abnormal for a healthy participant (Ferrari et al.

2008). This is likely to be due to kinematic crosstalk, where the axes defined by markers are out of plane with the axes about which the rotation is actually occurring, causing one rotation to be mistaken for another (Piazza & Cavanagh 2000). This is a well evidenced issue with PiG data and has been reported previously (Ferrari et al. 2008; McGinley et al. 2009). Internal/external rotation has often been reported as the most variable kinematic output (Karlsson & Lundberg 1994; Holden et al. 1997; Della Croce et al. 1999; Ferrari et al. 2008) and this is reflected in the results obtained in this study. There is little similarity in the pattern of excursion for internal/external rotation at the hip or knee between protocols, although the data are overlapping. The biggest differences in internal/external rotation were observed in swing with PiG estimating greater hip internal rotation than SCM, and PiG estimating knee internal rotation when SCM estimated knee external rotation.

In a previous study which compared five gait protocols (Ferrari et al. 2008), results showed hip internal rotation of more than 5° for only one of the five protocols. One protocol estimated external rotation in swing; however, the remaining three protocols measured a change from external to internal rotation of approximately 10°. Results from (Ferrari et al. 2008) also demonstrate four out of five protocols estimating knee external rotation in swing, with only one protocol measuring internal rotation. Further, (Czamara et al. 2015) measured four degrees of knee external rotation at the point of maximal knee flexion in swing. This supports the results from (Ferrari et al. 2008) and the results from the SCM model in the current study which demonstrated external rotation in swing. Further, evidence has suggested rotation may be more affected by soft tissue artefact (STA) than flexion or abduction (Manal et al. 2000). Reduced STA from the use of cluster markers in SCM may therefore account for the higher variability in rotation output from PiG when compared to SCM.

Generally, inter and intra-assessor reliability was good for both protocols. A notable exception was hip internal/external rotation for SCM, which consistently exhibited poorer ICC values than PiG. However, previous studies have noted lower reliability scores for internal/external rotation than flexion/extension and ab/adduction (Kadaba et al. 1989; Collins et al. 2009) and ICC is known to decrease when the range of physiological changes included is small (3-4° in this case). Pelvic tilt also demonstrated consistently lower ICC scores than other outputs for both PiG and SCM. This is most likely due to inconsistent identification of pelvic landmarks between sessions, as well as the aforementioned limited size of the physiological change involved. The superior/inferior position of the calibration markers on the anterior and posterior superior iliac spines (ASIS and PSIS, respectively) will directly affect the values for pelvic tilt. Identification of pelvic landmarks has demonstrated larger differences between assessors compared to other ALs (Della Croce et al. 1999) and could therefore account for the lower ICC values for pelvic tilt obtained in this study.

Assessor three demonstrated lower ICC values than assessor two for almost all outputs. These results could be expected as assessor three had limited experience with PiG and first used SCM during the familirisation session, whereas assessor two had five years' experience using PiG and three years' experience using SCM. Apart from pelvic outputs and hip flexion/extension, assessor three obtained higher ICC values with SCM than with PiG, suggesting that SCM may be more reliable than PiG for users with limited experience of clinical motion analysis protocols. However, assessor two achieved higher ICC values with PiG than with SCM. These results suggest that experience is likely to play a role in the reliability of motion analysis protocols. It may therefore be suggested that PiG is the most suitable model for experienced users in a controlled laboratory setting, but SCM is more suitable for novice users in a more routine clinical setting. Although some ICC results reported in this study are lower for SCM than PiG, they are still higher than the majority

reported for current clinical functional assessment methods which use observational analysis (Kawamura et al. 2007; Ong et al. 2008).

Overall, the protocols produced comparable results and it may therefore be suggested that a real-time protocol could serve as a suitable alternative to current clinical motion analysis methods for routine assessment.

One limitation of this study is that only healthy individuals were tested. PiG is commonly used by a number of clinical laboratories and is relied upon to provide guidance for intervention prescription including surgical planning (Schwartz & Rozumalski 2005). Currently, SCM has not been tested on pathological individuals and therefore it cannot yet be recommended for general clinical use to replace PiG for the assessment of gait in complex cases such as cerebral palsy. However, it could be recommended to provide an objective assessment method pre and post-intervention in an outpatient rehabilitation clinic or similar setting where the data are less critical. Further, only walking trials were tested. Kinematic values for walking are within certain limits which do not approach the maximum range of each joint. The results cannot predict what would happen if more extreme ROMs were tested such as stair climbing or sit to stand. Reliability results were limited by only two assessors with different experience levels completing intra assessor testing. Future studies should aim to complete intra assessor testing with a range of experience levels.

In conclusion, SCM was developed to address some of the issues which prevent use of motion analysis protocols for routine clinical assessment. Kinematic output was comparable to the current gold-standard and reliability results were better than current obserevational methods. PiG should continue to be used by experienced assessors for research or complex clinical cases; however, SCM is likely to be a suitable alternative for routine analysis in rehabilitation and visual feedback.

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Declaration of interest

There were no conflicts of interest regarding this study.

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Table 1. Anatomical reference frame definitions for the pelvis, right thigh, right shank and right foot. Left segments are defined in the same way, with the Z axis always being positive to the right. PSIS – posterior superior iliac spine; ASIS – anterior superior iliac spine; LE – lateral epicondyle; ME – medial epicondyle; LM – lateral malleolus; MM – medial malleolus; CA – calcaneus; FM – first metatarsal; VM – fifth metatarsal; HJC – hip joint centre; KJC – knee joint centre, AJC – ankle joint centre

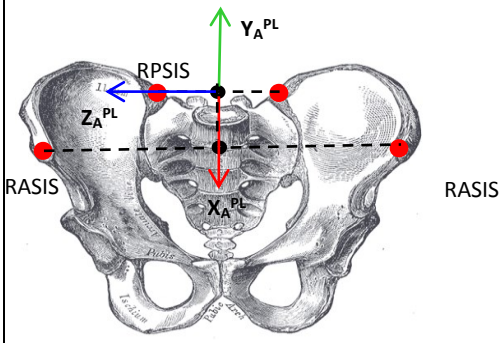
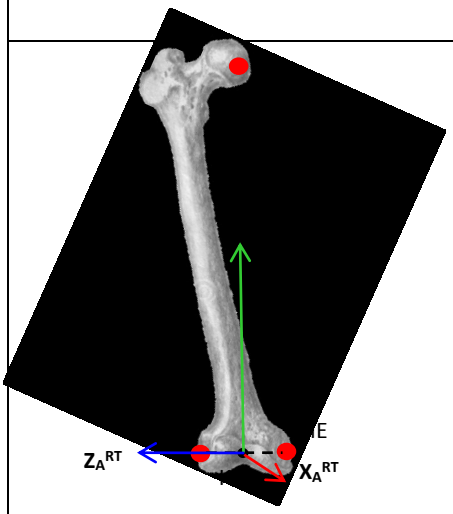
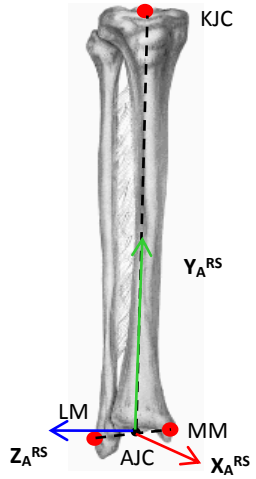
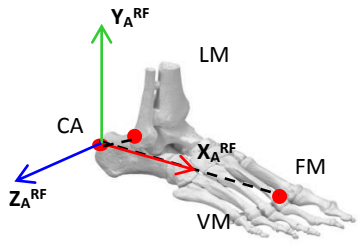
	Origin	Midpoint between LPSIS and RPSIS
	X_A^{PL}	Line between the midpoint of the RASIS and LASIS and the midpoint of the RPSIS and LPSIS
	Y_A^{PL}	Mutually perpendicular to X_A^{PL} and Z_A^{PL}
	Z_A^{PL}	Line between LASIS and RASIS and mutually perpendicular to X_A^{PL} and Y_A^{PL}
	Origin	KJC (midpoint between RME and RLE)
	X_A^{RT}	Mutually perpendicular to Y_A^{RT} and Z_A^{RT}
	Y_A^{RT}	Line between HJC and KJC
	Z_A^{RT}	Line between RME and RLE and mutually perpendicular to Y_A^{RT} and X_A^{RT}
	Origin	AJC (midpoint between RMM and RLM)
	X_A^{RS}	Mutually perpendicular to Y_A^{RS} and Z_A^{RS}
	Y_A^{RS}	Line between AJC and KJC
	Z_A^{RS}	Line between RMM and RLM and mutually perpendicular to X_A^{RS} and Y_A^{RS}
	Origin	CA
	X_A^{RF}	Line between CA and midpoint between FM and VM
	Y_A^{RF}	Mutually perpendicular to X_A^{FT} and Z_A^{FT}
	Z_A^{RF}	Line between CA and LM and mutually perpendicular to X_A^{FT} and Y_A^{FT}

Table 2. Mean (SD) as calculated by each model for hip, knee and ankle parameters for all subjects and corresponding *P* values (Wilcoxon Signed Ranks Test, $\alpha = 0.05$).

	PiG (Deg)	SCM (Deg)	Difference (Deg)	*P* Value
PELVIS				
Tilt excursion	7.4(2.7)	10.9(2.2)	3.5	**<0.001***
Obliquity excursion	10.1(3.8)	13.6(3.4)	3.5	**<0.001***
Rotation excursion	3.8(0.9)	7.8(2)	4	**<0.001***
HIP				
Flex/ext excursion	45.1(4.4)	40.1(5.1)	5	**<0.001***
Ab/adduction excursion	13.2(2.4)	16.2(2.5)	3	**<0.001***
Int/ext rotation excursion	26.9(10.8)	13.3(4.03)	13.6	**<0.001***
H1	-12.3(8.1)	-12.1(6.5)	0.2	0.313
H2	6.7(2.8)	8.4(2.9)	1.7	**<0.001***
KNEE				
Flex/ext excursion	60.8(5.6)	72.5(3.5)	11.7	**<0.001***
Ab/adduction excursion	19.2(7.6)	11.3(4.8)	7.9	**<0.001***
Int/ext rotation excursion	25.9(9.8)	13.3(3.9)	12.6	**<0.001***
K1	19.9(7.5)	18.5(8.01)	1.4	**0.007***
K2	59.01(14.1)	66.7(7.1)	7.69	**<0.001***
K3	16.1(8.3)	7.2(4.3)	8.9	**<0.001***
ANKLE				
Plantar/dorsiflexion excursion	29.4(2.9)	29.8(3.9)	0.4	0.386
A1	18.01(5.1)	18.2(4.7)	0.19	0.488
A2	-11.5(5.2)	-11.7(5.6)	0.2	0.792

H1 – peak hip extension, H2 – peak hip adduction in stance, K1 – peak knee flexion in loading response, K2 – peak knee flexion in swing, K3 – peak knee abduction in swing, A1 – peak ankle dorsiflexion and A2 – peak ankle plantarflexion*****statistically significant difference (Wilcoxon Signed Rank, $\alpha = 0.05$)

Table 3. Standard deviations and Intra Class Correlation Coefficient values for inter/intra assessor testing

	Inter Assessor SD		ICC		Intra Assessor SD				ICC			
	PiG	SCM	PiG	SCM	PiG		SCM		PiG		SCM	
PELVIS					A2	A3	A2	A3	A2	A3	A2	A3
Tilt	1.92	1.43	0.45	0.38	2.49	1.92	2.66	2.04	0.21	0.32	0.12	0.15
Obliquity	0.83	1.64	0.95	0.78	0.40	1.10	6.20	3.10	0.97	0.84	0.04	0.36
Rotation	0.83	1.43	0.96	0.81	0.60	0.83	0.56	9.92	0.95	0.93	0.88	0.05
HIP												
FL/EX	2.80	2.56	0.99	0.99	3.11	0.59	3.25	2.84	0.97	0.99	0.96	0.97
AB/AD	0.95	1.54	0.96	0.94	1.04	1.86	1.73	3.89	0.90	0.72	0.85	0.37
IN/EX	4.10	3.34	0.94	0.48	3.24	11.45	1.21	6.68	0.94	0.10	0.92	0.37
KNEE												
FL/EX	2.47	2.29	0.99	0.99	1.74	4.80	1.07	2.09	0.99	0.98	0.99	0.99
AB/AD	1.26	1.50	0.99	0.89	1.52	4.40	0.62	1.51	0.97	0.20	0.97	0.64
IN/EX	4.77	1.96	0.91	0.87	2.60	5.41	1.03	1.20	0.94	0.77	0.88	0.86
ANKLE												
FL/EX	2.93	2.26	0.93	0.98	0.69	3.42	1.55	3.14	0.99	0.87	0.98	0.92

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407 **Figure 1.** Comprehensive marker set comprised of SCM and PiG. SCM markers are circled. Single
408 markers were used for PiG and for calibration of SCM. Medial knee and ankle markers were
409 removed for dynamic trials

Figure 2. Landmarks used to define anatomical reference frames in the SCM protocol

Figure 3. Real-time feedback and measurement of kinematics using SCM

Figure 4. Mean kinematic output for all subjects' right legs. PiG (dashed) SCM (solid). Shaded grey areas represent mean ± 2SDs. Mean toe off is represented by vertical lines

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