Full length article

A standardised template for reporting lower limb kinematic waveform movement compensations from a sensor-based portable clinical movement analysis toolkit

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A B S T R A C T

Objectives: To develop a standardised template to support physiotherapist reporting of lower limb kinematic waveform data

Design: Within and between user agreement identification of movement compensation strategies.

Setting: University Health Board Physiotherapy Department

Participants: Fourteen individuals with anterior cruciate ligament reconstruction performed overground gait, double-leg squat, and stair ascent wearing body-worn sensors. Six users viewed 252 kinematic waveforms of hip, knee and ankle joint angles in the sagittal and frontal planes.

Main outcome measures: Between and within-user observed agreement and themes from movement analysis reports

Results: Between-user observed agreement for presence of a movement compensation was 0.6–0.9 for the sagittal plane and 0.75–1.0 for the frontal place. Within-user observed agreement was 0.57–1.00 for the sagittal plane and 0.71–1.00 for the frontal plane. Three themes and seven categories were identified from the waveform interpretations: Amount (qualitative and quantitative description), timing (phase, discrete time point, cycle), and nature (peak, range of motion, timing) of the compensation.

Conclusion: There was good agreement between users at identifying the presence of movement compensation from the kinematic waveforms, but there was variation in how movement compensations were described. An interactive report, a standardised template for interpretation of kinematic waveforms, and training to support the clinical application of a movement analysis toolkit are proposed.

Introduction

Analysing human movement is a core component of physiotherapy practice and is used to make judgements about how an individual is moving, what compensations they are using and what treatment techniques need to be applied to improve performance, recovery and/or prevent injury [1,2]. However, analysing human movement is complex as three planes of motion need to be considered (sagittal, frontal and transverse) across multiple joints and the tasks analysed vary in complexity according to the individual's functional needs [2,3]. This poses a challenge in clinical practice where physiotherapists have traditionally relied on observational analysis to assess human movement. Observation can be subjective and has poor accuracy and reliability, especially in in-

experienced raters [4,5]. Traditional observational methods would not allow a physiotherapist to accurately observe multiple joints and multiple planes simultaneously across a range of functional tasks.

Growth in new technology has led to the development of portable wearable sensors that consist of gyroscopes, accelerometers, magnetic sensors and algorithms to quantify human movement [6]. Sensors may provide a solution to limitations of observational methods. They accurately and reliably measure lower-limb joint motion [7] and can be used in the clinical setting by physiotherapists who do not need to be technology experts [8]. Sensor-based movement analysis generates large volumes of kinematic data for multiple planes of motion and joints simultaneously [9]. For ease of use in the clinical setting, and for the patient

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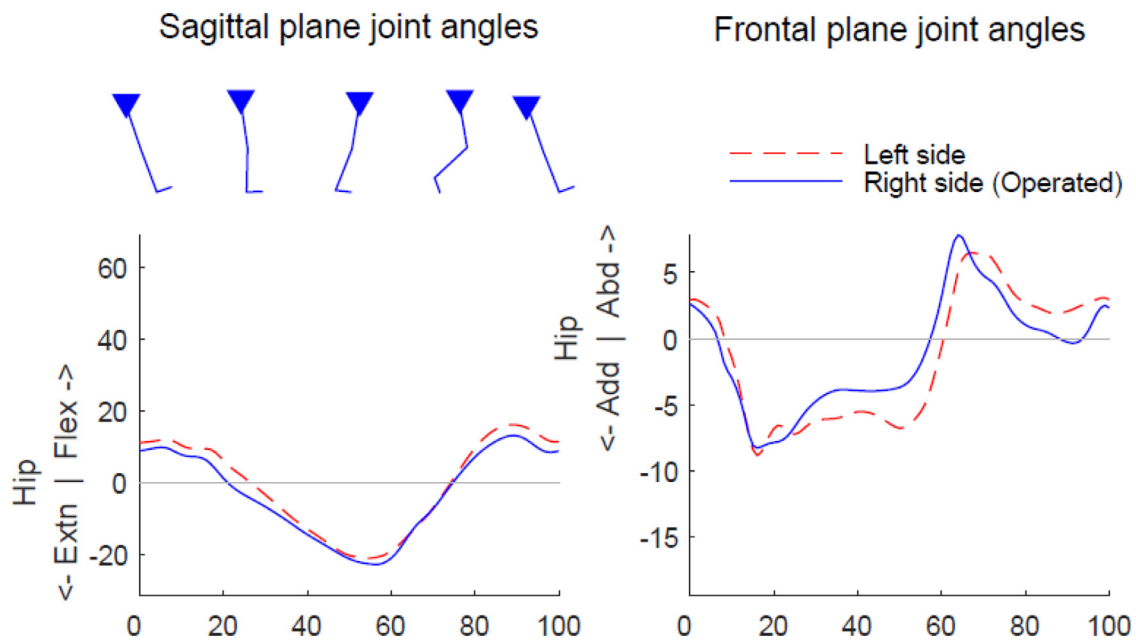 *E-mail address:* al-amrim@cardiff.ac.uk (M. Al-Amri).

Fig. 1. Examples of waveforms and stick figures from a movement analysis report.

to access at home, these data need to be presented in a user-friendly manner. Summary statistics can be generated to provide a quantitative description of motion but visually inspecting waveforms of movement cycles provides additional information about how an individual is performing during a task that can inform treatment selection. However methods which standardise the subjective interpretation of observational analysis are needed. To this end, we designed a movement analysis report that displays hip, knee and ankle joint angle waveforms in the sagittal and frontal planes, along with a stick figure representing the movement performed and a summary of performance measures (Fig. 1 and supplementary material).

The sensors and movement analysis report form a portable toolkit that can be used in the clinical setting by physiotherapists and patients, who make their own interpretation of the report and use this to inform the treatment plan. Interpretation of the movement analysis report has two components: identifying if a compensation strategy is present, and describing the compensation. Physiotherapists need to be skilled in both components to ensure accurate and consistent clinical decision making [10]. Before this movement analysis report can be implemented in practice it is essential to determine how the kinematic waveforms are interpreted by physiotherapists and their consistency at interpreting them.

The aim of this study was to develop a standardised template to support physiotherapist reporting of lower limb kinematic waveform data. This was achieved by firstly, evaluating between- and within-user agreement in the identification of movement compensation strategies and secondly, by identifying how users described these movement compensations for the hip, knee and ankle in the sagittal and frontal plane.

Methods

Design

A between- and within-user agreement design and quantitative content analysis, to evaluate agreement in the identification in the compensation strategies and how users described the movement compensations. Ethical approval was granted by the Wales Research Ethics Committee 3 (10/MRE09/28).

Participants

A convenience sample of 14 individuals receiving physiotherapy following anterior cruciate ligament reconstruction were recruited from one University Health Board. This group of individuals frequently have persistent movement compensation strategies despite rehabilitation and are at risk of re-injury [11,12,3]. To be included individuals needed to be aged over 18 years, independently mobile, undergoing physiotherapy treatment following their anterior cruciate ligament reconstruction, read and write English and be able to give written informed consent. The exclusion criterion was multiple ligament surgery or the presence of another musculoskeletal or neurological conditions that impacted their movement. Participants were between 6 weeks to 52 weeks post-surgery, and represented the broad range individuals that receive physiotherapy following this surgery. Participants underwent one sensor-based motion analysis session in the physiotherapy department.

Sensor-based motion analysis

Kinematic data were collected using seven MTw2 trackers (Xsens Technologies B.V., Enschede, The Netherlands) that were secured using elasticated Velcro straps on each upper thigh (centrally and halfway between the greater trochanter and lateral epicondyle of the knee), each lower leg (proximal medial surface of the tibia), the dorsum of each foot and one centrally over the sacrum, in accordance with Xsens instructions [13]. The same physiotherapist set up the trackers on each appointment. The MTw2 trackers were calibrated prior to beginning data collection, allowing MVN BIOMECH studio software (version 4.4) to establish the relation between segment and tracker orientations. The participant was asked to stand in a static N-pose, for ∼30 s as per the user manual instructions [13]. The patient performed the following tasks; over-ground gait, double-leg squat and stair ascent. For each task data were exported to a *.mvnx file.

Movement analysis report

The movement analysis report was generated using custom-written code [14] (Matlab version 2015a; The MathWorks Inc., Natick, MA,
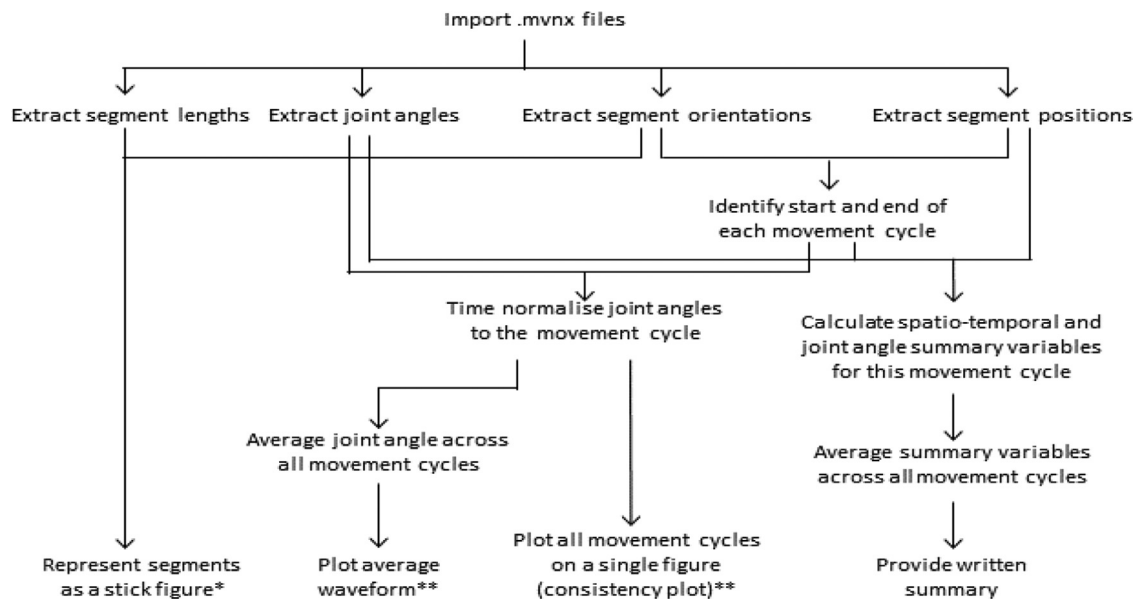
Fig. 2. Flow chart summarising the generation of the movement analysis report. *Stick figures personalised to the individual movement were presented in the sagittal plane only and presented at 1, 25, 50, 75 and 100% of the movement cycle, to provide a visual representation of the position of the lower limb. **Waveforms were plotted for the operated and non-operated limb.

USA). The physiotherapist was required to input details about the patient such as participant code, side of the involved limb side, date, visit number and the tasks performed, select the relevant *.mvnx files and then run the Matlab script that automatically produced the report, as summarised in Fig. 2. The first page of the report presented a summary of performance measures (walking speed, stride duration, stance time, swing time, and stride length for overground gait; squat duration for double-leg squat and step duration for stair ascent). Subsequent pages presented the hip, knee and ankle joint angle waveforms in the sagittal and frontal planes time normalisation to the duration of a cycle . Waveforms were presented for the injured and non-injured legs. On separate pages, waveforms were presented before and after being averaged across a minimum of six movement cycles. One report was generated for each participant (total of 14 reports). An example report is provided in supplementary material. Movement cycles were defined in Matlab using a custom-written script. For the double-leg squat, the start and end of the movement cycle was defined as the start and end of knee flexion. For stair ascent, the start of each movement cycle was the local minima in vertical distance between the pelvis and the foot segments, i.e., when the foot was closest to the pelvis. The end of each movement cycle was the start of the next cycle. For walking, foot strike was identified using the anterior-posterior position of the foot relative to the pelvis, as described by Zeni et al. [15]

Two hundred and twenty-five kinematic waveform graphs were generated across 14 movement analysis reports which were analysed independently by six users and three users analysed the reports a second time one week later. The sample size was determined using power of 80%, alpha 0.05, K1=0.3 and K2=0.9 [16]. For each report there were 18 parameters for the user to interpret: hip, knee, and ankle angle in the sagittal and frontal plane for overground gait, double-leg squat and stair ascent. For each parameter, users were instructed to look at the graph showing average waveform for each participant. They were also provided with the individual movement cycle traces and could look at these if they wished, but were not instructed to do so. Five users were physiotherapists, all with varying levels of experience (range 1 to 24 years) in biomechanics and in rehabilitating individuals with anterior cruciate ligament reconstruction and one user was a clinical movement scientist. Within user agreement was evaluated using data from one experienced physiotherapist and two novices in movement analy-

sis. A convenience sample of raters was used. Four of the physiotherapists had over 10 years of clinical experience and one physiotherapist had less than 5 years clinical experience. Two of the physiotherapists had over 10 years' experience in laboratory movement analysis and three had less than 5 years experience. The movement scientist has over 10 years experience of laboratory movement analysis within this specialism.

Users were provided with the time post-surgery for each of the participants but no other clinical details. Users were instructed to document yes or no if they thought a movement compensation strategy was present for each parameter. If they thought a compensation strategy was present, then they were required to describe it using text. Prior to data collection the user's met with the research assistant (MF). Training was given on how to interpret the waveform, but the individual was left to determine if there was a compensation present, there was no standard criteria but raters were advised that there wasn't necessarily a compensation strategy present on all of the waveforms.

Between- and within-user agreement

Between and within-user agreement were quantified using observed agreement [17] Gwet's agreement coefficient with first-order chance correction (AC1) [18], and weighted Cohen's kappa [19]. Observed agreement was calculated as the amount of observed agreement (i.e. objects that pairs of users assigned to the same or similar categories) divided by the amount of possible agreement (i.e. objects that pairs of users could have assigned to the same categories). However, even if the users rated reports without looking at the report, there would be some agreement caused by chance. Cohen's kappa and Gwet's AC1 inter-user agreement measures the agreement that exceeds that caused by chance, such that a value of zero would indicate agreement no better than by chance, and a value of unity would indicate perfect agreement. Kappa [20] has the paradox of giving smaller values when there is high agreement in one category. Gwet's AC1 [18] does not have this paradoxical property.

For chance-corrected agreement a value <0.2 was considered as poor agreement, 0.21–0.4 as fair, 0.41–0.6 as moderate, 0.61–0.8 as strong and >0.80 as near-complete agreement [21]. Matlab software (The MathWorks Inc.) was used to calculate between and within- user

Table 1

Number of times (n) a compensation strategy was identified as present and between-user agreement for the presence of a compensation strategy.

Joint	Planes	Walk (GAIT)				Double-leg squat (DLS)				Stair ascent (SA)			
		n	Gwet's AC1	Light's Kappa	Observed Agreement	n	Gwet's AC1	Light's Kappa	Observed Agreement	n	Gwet's AC1	Light's Kappa	Observed Agreement
Hip	Sagittal	27	0.32	0.32	0.61	35	0.53	0.51	0.76	44	0.20	0.25	0.60
	Frontal	70	0.66	Nan	0.75	81	0.92	Nan	0.93	82	0.95	Nan	0.95
Knee	Sagittal	58	0.43	0.26	0.68	42	0.73	0.79	0.90	60	0.47	0.25	0.69
	Frontal	75	0.81	Nan	0.84	81	0.92	Nan	0.93	84	1.00	Nan	1.00
Ankle	Sagittal	53	0.31	0.24	0.63	34	0.45	0.45	0.71	57	0.33	0.24	0.62
	Frontal	75	0.76	Nan	0.81	72	0.75	0.43	0.81	80	0.90	Nan	0.91

Table 2

Within-user agreement for the presence of a compensation strategy.

		Overground gait				Double-leg squat				Stair ascent			
		R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4
Hip	Sagittal plane	0.86	0.86	0.86	0.78	0.71	0.86	0.79	0.93	0.79	0.93	1.00	0.64
	Frontal Plane	0.93	1.00	0.71	0.86	1.00	1.00	0.93	1.00	0.93	1.00	1.00	0.86
Knee	Sagittal plane	0.79	1.00	0.93	0.71	0.79	1.00	1.00	0.79	1.00	1.00	0.86	0.79
	Frontal Plane	0.93	1.00	1.00	1.00	1.00	1.00	0.93	1.00	1.00	1.00	1.00	0.93
Ankle	Sagittal plane	0.57	1.00	0.93	0.64	1.00	0.93	1.00	0.93	0.86	1.00	0.64	0.64
	Frontal Plane	1.00	1.00	0.86	1.00	1.00	1.00	0.93	1.00	1.00	1.00	1.00	0.93

Table 3

Definitions of categories and codes.

Theme	Category	Definition	Examples of codes used
Amount	Qualitative description	A description in words of the size or magnitude of the compensation strategy.	Decreased, reduced, too little, lack of, less slight, minimal, subtle, increased, greater, too much, early, rapid, late, delay in
	Quantitative description	The size or amplitude of the compensation described in numbers.	Degrees e.g. 10°
Nature	Peak (maximum)	An alteration in the peak (maximum) on the waveform	Peak, maximum
	Range of Motion (ROM)	An alteration in the range of motion of the waveform.	Range of motion, ROM, range
	Timing	An alteration in the timing of the waveform.	Timing, asynchronous, rapid, delayed
Timing	Cycle	A compensation strategy that is identified as happening throughout the entire movement cycle:	Throughout cycle, during squat, across full movement cycle, throughout the whole task
	Phase	A compensation strategy that is identified as happening during a specific phase of the movement cycle.	Stance phase, initial descent phase, step up phase, through decent, swing phase
	Discrete Time Point	A compensation strategy that is identified as happening at a discrete time point within the movement cycle.	Initial contact, mid stance, toe off, at full squat depth, at foot contact with step

agreement. The Matlab functions used were based on Girard et al. 2008 [22].

Quantitative content analysis

Quantitative content analysis was used to create categories for the purpose of understanding and describing the written text about the movement compensation strategy [23,24]. Data were managed using NVivo 12 software (QSR International Pty Ltd). Firstly, two reviewers independently identified preliminary codes, categories and themes, and agreed these with a third reviewer. The two reviewers then independently coded one of the tasks (double-leg squat) and agreed on the coding. Codes were identified inductively. One reviewer coded all of the scripts and this was checked by a second reviewer. Any disagreements were discussed and agreed upon by a third reviewer. The frequency that each category was reported on was measured [24,25,23]. The codes, categories and themes were used to create a standardised template for reporting on the kinematic waveforms.

Results

Between- and within-user agreement

. For each activity at each joint and in each plane the number of times a movement compensation strategy was identified is shown in Table 1.

Between-user Kappa, Gwet's AC1 and observed agreement are shown in Table 1. Three users analysed the reports a second time one week later. Within-user Kappa, Gwet's AC1 and observed agreement are shown in Table 2.

Quantitative content analysis

Three themes were identified in the users' descriptions of movement compensation strategies: amount, nature, and timing. The definitions of the themes are:

- Amount: Description relating to the size or magnitude of a compensation strategy
- Nature: Description relating to the type of compensation strategy
- Timing: Description relating to when the compensation strategy occurred in the movement cycle.

Within these themes, seven categories were identified, the definitions of which and codes that were used are given in Tables 3.

Across all the users the themes 'amount', 'nature' and 'timing' were reported 1689, 968, and 1338 times, respectively. The number of times that each category within these themes was reported is provided in Table 4. There were cases when the interpretation was ambiguous and terminology such as altered, asynchronous and opposite movement were used.

Table 4
The number of times that each category was reported across all users and planes.

	Amount		Nature			Timing		
	QualitativeDescription	QuantitativeDescription	Peak (Maximum)	Range of Motion (ROM)	Timing	Cycle	Phase	Discrete Time Point (DTP)
Walk (GAIT)	553	44	106	115	107	63	303	132
Double Leg Squat (DLS)	454	35	79	96	60	159	234	84
Stairs Ascent (SA)	568	35	132	108	165	96	86	171
Total	1575	114	317	319	332	318	633	387

Discussion

In this study we used wearable sensors to measure the kinematics of three functional activities performed by 14 individuals with anterior cruciate ligament reconstruction in a physiotherapy clinic. The kinematics were summarised in a custom-made report that was provided to six users who were asked to identify the presence of movement compensation strategies at the ankle, knee and hip joints in the sagittal and frontal planes. Overall, there was good agreement between the users identifying the presence of kinematic compensations, but there was variation in how these were qualitatively described. This could lead to differences in clinical decision making and treatment planning.

The first aim of this study was to evaluate the between- and within-user agreement for identifying the presence of movement compensation strategies from kinematic waveforms for overground gait, double-leg squat and stair ascent. The findings indicated that between-user agreement ranged from moderate to near-complete agreement. Regardless of statistical technique, between-user agreement was higher for movement compensation strategies in the frontal plane than in the sagittal plane and for analysis of knee joint motion than hip or ankle joint motion. Within-user agreement was near-complete agreement across all activities, planes of motion and joints. This suggests that there would be consistency in decision making if the same user interpreted a report over time. These findings are similar to previous studies that have evaluated between-user agreement for identifying kinematic movement compensations. Nieuwenhuys et al. [26] found substantial to almost-perfect agreement between and within experienced and inexperienced users interpreting three-dimensional gait joint motion data from children with spastic cerebral palsy collected in a motion analysis laboratory. Wang et al. [27] found moderate agreement between experienced surgeons identifying gait problems in children from three-dimensional gait motion analysis (kinematics, kinetics, electromyography and video) data. However, in the studies by Nieuwenhuys et al. [26] and Wang et al. [27], users were only required to state if a gait problem was or was not present and were not required to describe this. Brunnekreef et al. [28] found moderate reliability between experienced and inexperienced users interpreting video footage of gait in adult orthopaedic patients using a standardised template, but users were not given waveform data. The standardised template was based around the presence or absence of specific gait deviations and their timing (stance or swing phase of gait) and is therefore not comparable with the current study.

The second aim of this study was to identify how users described any identified movement compensation. Three themes were identified in the descriptions: the amount of compensation, the nature of the compensation, and the timing of the compensation. These themes should be included in any interpretation of the report to avoid ambiguity and inconsistent clinical decision making. The theme that was most commonly reported was the amount of compensation. Two categories were identified within this theme: qualitative description and quantitative description, with the former being most commonly reported. Providing a quantitative description of the amount of compensation alongside a qualitative description (e.g. too much, too little) may increase objectivity and help set targets for monitoring measurable change. Our results showed that users did not commonly do this. The next version of the report will encourage this by allowing the user to request quantitative data on key parameters. Furthermore, in the next version of the report symbols will be used to assist with interpretation of the qualitative description e.g. an upward arrow for too much.

The second most common theme to be reported was 'timing', which was a description about when the movement compensation strategy occurred. Three categories were identified: phase, discrete time point, and cycle. Within this theme a large variety of codes were used, which opened up the potential for inconsistency in reporting between users. For example, in the stair ascent task, events were described as lifting leg phase or swing phase and floor in contact with step phase or stance phase. Furthermore, in the double-leg squat task, the terms peak knee flexion and at maximum squat were used inter-changeably. Standardisation of terminology around phases and discrete time points within movement cycles would support users to be precise in their reporting. A greater number of images showing the key events for each task may help users to be specific in their interpretation, particularly for discrete time points.

The final theme, which was least commonly reported on, was the nature of the compensation strategy and this had three categories: range of motion, peak, and timing. The coding used for these categories had a limited corpus of terms. There were a number of instances when the interpretation of the nature of the compensation was ambiguous. For example, 'reduced ankle flexion throughout', 'too little abduction throughout', 'increased knee abduction', and 'more ankle adduction throughout'. Based on these examples, it is not clear if the compensation was manifest in the range of movement or the peak angle. To prevent ambiguity, user's need to be encouraged to specify the nature of any compensation in their interpretation.

The findings from our study are unique as users had to distinguish between kinematic waveforms that did and did not have movement compensations, and users had to provide a description of their interpretation, which has not been explored in previous studies. We were interested in the consistency of this decision making between raters as it is not known if differing participants did actually employ a compensation strategy. It is this component of the interpretation that could result in variation and inconsistency in clinical decision making. Based on our findings we propose implementing a template to standardise the terminology and reporting in future versions of the movement analysis report, as displayed in Fig. 3. User training is recommended to standardise terminology used in interpretation based on the amount, nature and timing of the movement compensation strategies. The next iteration of the movement analysis report will allow the user to interact with an electronic version of the report to improve interpretation and include the following features:

- Allow the user to insert icons or codes onto the graphs to annotate the amount and nature of the compensation strategy
- Allow the user to enlarge segments within the waveform or have drawing tools to highlight timing of when the compensation strategy is occurring.
- Allow the user to request number data on the amount of compensation for key parameters.
- Allow the user to select the cycles that they want to include in the graphs of the average waveform
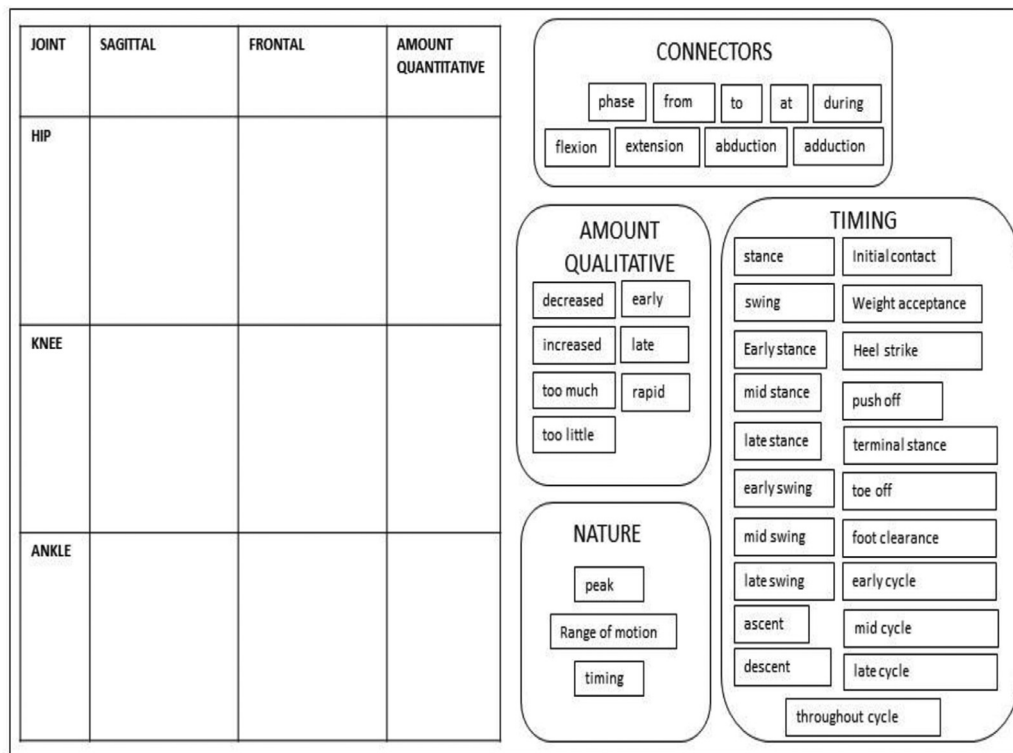
JOINT	SAGITTAL	FRONTAL	AMOUNT QUANTITATIVE
HIP			
KNEE			
ANKLE			

CONNECTORS

phase	from	to	at	during
flexion	extension	abduction	adduction	

AMOUNT QUALITATIVE

decreased	early
increased	late
too much	rapid
too little	

NATURE

peak

Range of motion

timing

TIMING

stance	Initial contact
swing	Weight acceptance
Early stance	Heel strike
mid stance	push off
late stance	terminal stance
early swing	toe off
mid swing	foot clearance
late swing	early cycle
ascent	mid cycle
descent	late cycle
	throughout cycle

Fig. 3. Standardised terminology and temple for interpretation of kinematic waveforms.

• Provide a series of pictures on each graph to illustrate the movement cycle for each activity.

Limitations

Users were not given specific guidance on when differences in the waveform were is a possibility that when small deviations in the waveform were present, there may have been differences across users as to whether these were or were not considered a compensation. Differences in the scales used to display the sagittal and frontal plane data mean that differences in waveforms in the frontal plane looked more pronounced to the user, and therefore may have been more likely to be viewed as a compensation strategy than differences of a similar magnitude in the sagittal plane. It was not the aim of this study to determine the clinical relevance of any identified movement compensation strategies, and this remains an important avenue for future research.

Conclusions

The sensor-based portable movement analysis toolkit gives physiotherapists and patients access to multi-planar kinematic data in real-time in the clinical setting, and these data can be used for planning treatment and monitoring rehabilitation progress. Our findings indicate that although there was a good level of agreement between and within users to identify movement compensation strategies, there was variation in the interpretation of the movement compensation, which could impact on clinical decision making. This is the first study to provide standardised terminology for the interpretation of movement analysis waveforms. User training on interpretation of the kinematic waveforms is recommended, and interpretation should be standardised to describe the amount, nature and timing of a compensation strategy. A digital version of the report is now being created that will be included in the next iteration of the toolkit to assist users in providing a consistent description of movement compensation strategies and accurate clinical decision making based on kinematic data.

Conflicts of interest

There are no conflicts of interest

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ipemt.2021.100001.

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