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Cervical spine kinematics measured during rugby union scrums: Reliability of optoelectronic and electromagnetic tracking systems

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Abstract: Measuring cervical spine kinematics in rugby scrummaging is important from an injury prevention perspective. However, choosing an appropriate measurement system is challenging. Since reliability of a measurement system is critical for meaningful interpretation of results, this study evaluated test-retest reliability of an electromagnetic tracking and optoelectronic motion capture system for measurement of cervical spine kinematics during scrummaging. Reliability of joint kinematics at discrete time points was evaluated using intraclass correlation coefficients (ICC), standard error of measurement (SEM), and minimal detectable change (MDC). Reliability of kinematic curves was assessed using coefficient of multiple correlations (CMC) and standard deviations (curve SD). In both systems, seven ICC values were considered to be excellent (>0.75), while two were fair to good (0.44–0.66). Minimal detectable change values for flexion/extension were found to be higher than for other movement directions, and CMC values were only moderate. Overall, reliability was comparable in both systems.

Subjects: Applied Sport Science; Kinesiology; Sports Technology and Engineering; Biomechanics and Human Movement Science; Sports Injury; Rugby

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The authors have collaborated on investigating the reliability of motion tracking devices for the measurement of cervical spine kinematics during scrums. This study is part of a larger research project investigating spinal kinematics during scrummaging with particular focus on how the complexity of the scrum task (e.g. machine-based scrummaging versus opposed scrummaging) affects spinal kinematics and possibly contributes to spinal injuries.

PUBLIC INTEREST STATEMENT

Rugby scrums carry high risk of injury and understanding injury mechanisms may help develop injury prevention strategies. It is particularly important to prevent neck injuries given the potential catastrophic consequences. For this purpose, it is important to measure head and neck motion patterns during scrums, but taking these measurement is challenging. While different measurement systems have different advantages and limitations, reliability is an important consideration when selecting the method to measure head and neck kinematics. Therefore, this study investigated reliability of two different systems, optical and electromagnetic tracking, during simulated scrums. The findings revealed that both devices had comparable reliability, meaning that either method can be used in future studies depending on the specific research question. From a movement repeatability perspective, neck movements in flexion/extension were more variable than in other directions, which should be considered in future studies, particularly those measuring kinematics before and after an intervention.

| **Keywords:** motion capture; neck; scrummaging; reliability

1. Introduction

In rugby union, a scrum occurs after a minor infringement and normally involves eight players from each team pushing against each other to compete for ball possession (World Rugby, 2018). The scrum is physically demanding and carries a high risk for injury (Fuller, Brooks, Cancea, Hall, & Kemp, 2007), particularly to the spine (Brooks, Fuller, & Kemp, 2005).

Understanding mechanisms of scrum-related spine injuries may assist in developing injury prevention programs, which appears particularly important for the cervical region due to the catastrophic consequences of injuries to the neck (Hutton et al., 2016). For the cervical spine, two potential injury mechanisms have been proposed. First, it has been suggested that scrum-related cervical spine injuries were due to flexion of the neck that is forced beyond physiological range (Scher, 1982). The second mechanism proposed has been described as “buckling” where the straightened cervical spine is compressed under axially directed loads (Torg, Pavlov, O’Neill, Nichols, & Sennett, 1991). The descriptions of these distinct mechanisms suggest two different cervical spine movement patterns may contribute to cervical injuries, but this remains unclear (Dennison, Macri, & Cripton, 2012; Trewartha, Preatoni, England, & Stokes, 2015). Therefore, it is important to investigate cervical spine kinematics during the scrum task.

However, choosing the most appropriate measurement system to measure cervical spine kinematics during scrums is challenging. Many different measurement systems exist, each with advantages and limitations. Optoelectronic motion capture (OMC) systems are widely used for human motion analyses (Chiari, Croce, Leardini, & Cappozzo, 2005), due to their accuracy and reliability (Eichelberger et al., 2016; Windolf, Götzen, & Morlock, 2008). Optoelectronic motion capture has been used to investigate kinematics in one-man scrums performed against a scrum machine (Wu, Chang, Wu, & Guo, 2007), but not in field-based and/or contested scrums. In field-based, contested scrums, where the cervical region is obscured by multiple players, a portable, non-optical measurement system is required. Inertial measurement units have been used to measure spinal kinematics in contested scrums (Swaminathan, Williams, Jones, & Theobald, 2016a), but they typically do not measure spatial position, rather orientation. Measuring position is important because motion of the cervical spine can occur if the head translates in a sagittal or transverse plane relative to the thorax, even if the orientation of the head does not change (Penning, 1978), thereby possibly influencing injury risk.

Alternatively, cervical spine kinematics during scrums could be measured using electromagnetic motion tracking (EMT) systems, which are portable, do not require body parts to be visible and can measure spatial position. The accuracy and precision of EMT systems have also been shown to be excellent, with measurement error ≤ 5 mm (Frantz, Wiles, Leis, & Kirsch, 2003). However, measurement quality decreases with increasing distance between the antenna emitting the electromagnetic field and the sensors (Frantz et al., 2003).

To select the most appropriate measurement system, it is necessary to know the reliability of each system during the specific task of interest (Atkinson & Nevill, 1998). Therefore, the aim of the present study was to concurrently evaluate test-retest reliability of an OMC and EMT system to measure cervical spine kinematics during simulated one-man scrums.

2. Methods

2.1. Participants

Nine healthy male adults, free from current injury and with no history of neck or shoulder surgery, were included (Walter, Eliasziw, & Donner, 1998). Both player and non-player participants were included to represent a range of abilities (Portney & Watkins, 1993). Four participants were club-

level front row players (24.2 ± 3.5 years; 179.6 ± 9.5 cm; 104.0 ± 10.6 kg), and five were non-players (26.8 ± 1.4 years; 174.2 ± 3.9 cm; 74.9 ± 13.6 kg). Participants provided written informed consent prior to participation and the study was approved by the institution's Human Ethics committee.

2.2. Instrumentation

Cervical spine kinematics, considered as the movement of the head relative to the thorax, were recorded using a six degrees-of-freedom EMT system (Polhemus Liberty, Polhemus, Colchester, VT, USA). One sensor was attached to the sternal notch (representing the thorax) and one sensor to an individually moulded thermoplastic mouthpiece that extended out of the mouth (representing the head). The EMT system's antenna was placed approximately 60 cm from participants. Concurrently, cervical spine kinematics were recorded using a 12-camera OMC system (Vicon, Oxford, UK) with 12 reflective markers. Both measurement systems were synchronised using a Telemetry Relay Repeater and sampled at 240 Hz. To register reference frames for both measurement systems during data processing, three additional reflective markers were placed on the EMT system's antenna (Cartesian origin).

Due to the sensitivity of EMT systems to metal (LaScalza, Arico, & Hughes, 2003), a custom-made wooden scrum-machine was used, with pad height replicating commercial scrum sleds. The scrum-machine was weighted using gravel bags with Velcro attached to the under surface to prevent lifting and sliding.

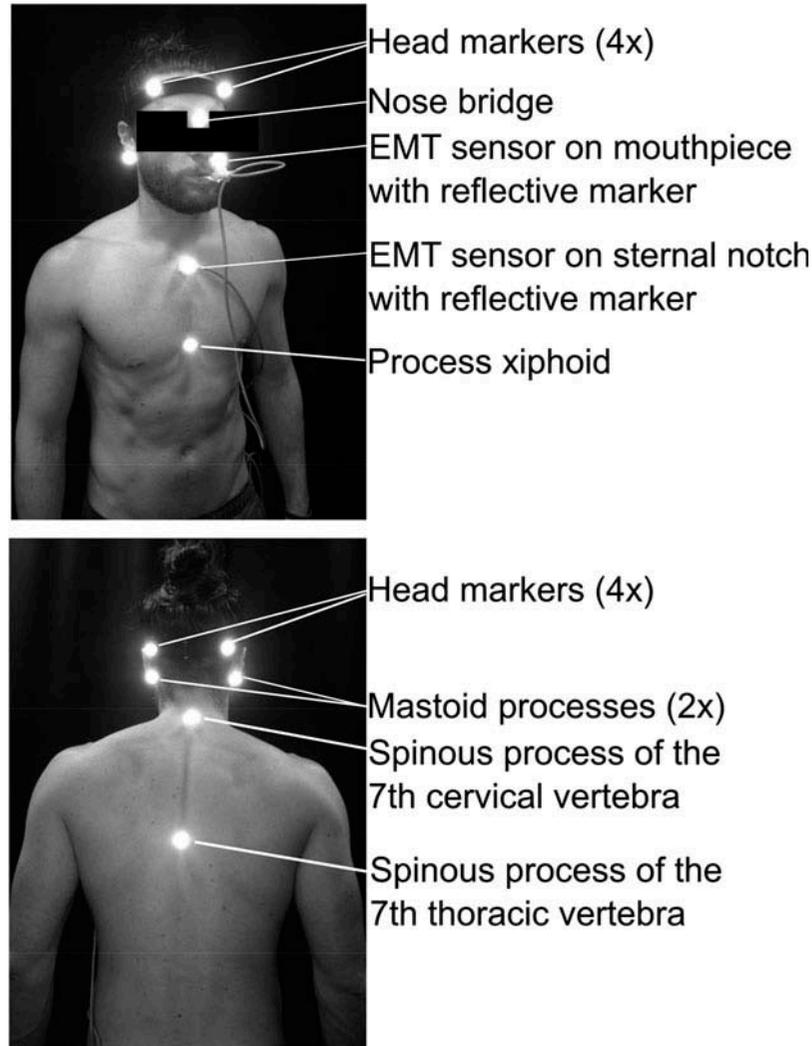
2.3. Procedure

Participants first performed a standardised warm-up routine consisting of 5-minutes of cycling at a moderate intensity, body-weight squats, resisted shoulder abduction, and head flexion/extension, lateral flexion and rotation. After warming up, two EMT sensors were attached to the sternal notch and to the mouthpiece (Figure 1). Six anatomical landmarks (left and right mastoid processes, nose-bridge, process xiphoid and the spinous processes of the 7th cervical (C7) and thoracic (T7) vertebrae) were palpated and then digitised using a third EMT sensor mounted on a stylus (Mills, Morrison, Lloyd, & Barrett, 2007). Orientations and locations of all three sensors were recorded along with location of each anatomical landmark, such that it was possible to later calculate location of each anatomical landmark relative to the sensors. A reflective marker was attached to each landmark immediately after digitisation to ensure consistency in landmark identification between the two systems. Reflective markers were then attached to the head (four markers on a headband) and to both EMT sensors (Figure 1). Next, a static trial was recorded, where participants were asked to adopt the trunk, neck and head position they considered as neutral in an upright position. Following the static trial, markers from the nose-bridge and mastoid processes were removed, as these would be occluded during scrums. Non-player participants were taught basic scrum technique according to the most recent scrum law ("crouch, bind, set"), and participants were instructed to perform scrums as consistently as possible. Player participants were asked to perform scrums with intensity comparable to a contested scrum, and non-players were asked to perform scrums at the highest comfortable intensity. Participants performed practice trials until familiar with the technique, apparatus, and protocol, before data were recorded from seven trials (Walter et al., 1998). Participants had 1–2 min' break between each trial to minimise effects of fatigue (Cazzola, Preatoni, Stokes, England, & Trewartha, 2015).

2.4. Data processing

Data from the EMT system were processed using a custom-written MATLAB script (version R2014a, MathWorks Inc., Natick, MA, USA) to reconstruct trajectories of digitised anatomical landmarks relative to the two sensors (Mills, Morrison et al., 2007). Marker data from the OMC system were then processed, which involved removing ghost markers and filling gaps if necessary, using Vicon Nexus software (version 2.2.1, Vicon, Oxford, UK). Virtual markers on the nose-bridge and mastoid processes were reconstructed in Vicon BodyBuilder (version 3.6.2, Vicon, Oxford, UK) by using their locations relative to the head markers recorded during the static trial. Then, using the markers placed on the antenna, virtual markers representing the EMT system's global coordinate system

Figure 1. Sensors and reflective markers placement.



(GCS) were created. These virtual markers were used to transform OMC data to align with the EMT system's GCS. The transformations were performed with a custom-written MATLAB script that relied on homogeneous transform calculations (Craig, 2005). Aligning global coordinates for both systems resulted in one common GCS for both sets of data. A second-order, zero-lag Butterworth filter with 6 Hz cut-off frequency was applied to both data sets (Swaminathan, Williams, Jones, & Theobald, 2016b).

Local coordinate systems were then created in both data sets for the head (LCS_{Head}) and thorax (LCS_{Thorax}) using the anatomical landmarks (Table 1). For the origin of LCS_{Head} , a virtual marker was created as the mid-point between mastoid processes, and served as a representation of the first cervical spinous process (C1). Relative orientation between the head and thorax was then calculated and expressed as X-Y-Z" Cardan angle sequence representing (1) flexion/extension (FE), (2) lateral flexion (LF) and (3) axial rotation (ROT) (Robertson, Caldwell, Hamill, Kamen, & Whittlesey, 2014). The joint angle offset from natural upright posture was removed from all scrum trials using the average rotation matrix from the static trial (Koning, Krogt, van der Krogt, Baten, & Koopman, 2012). For analysis purposes, data from all trials were extracted from a 6 s time window that was based on the instant of impact. Impact with the scrum machine was identified for each trial from OMC data as the instant where the C7 marker stopped moving in the primary direction of scrummaging. The beginning of a trial (T1) was then set as 1 s before impact (T2). Subsequently,

Table 1. Generation of local coordinate systems for the head (LCS_{Head}) and thorax (LCS_{Thorax})

LCS _{Head}	<p>Origin: C1 X_{Head}: + Right Perpendicular to Y_{Head} and Z_{Head} Y_{Head}: + Dorsal C1—Nose Bridge Z_{Head}: + Caudal Perpendicular to the plane formed by Nose Bridge, C1, and Right Mastoid Process</p>
LCS _{Thorax}	<p>Origin: T7 X_{Thorax}: + Right Perpendicular to the plane formed by T7, Process Xiphoid, and C7 Y_{Thorax}: + Dorsal T7—Process Xiphoid Z_{Thorax}: + Caudal Perpendicular to X_{Thorax} and Y_{Thorax}</p>

the sustained push (T3) and the end of the trial (T4) were defined as time points at 2.5 s and 5 s after impact, respectively. The T1–T4 times were set in the EMT data using frame numbers from OMC data.

2.5. Statistical analysis

First, descriptive statistics (mean \pm standard deviation (SD)) were calculated for each movement direction (FE, LF and ROT) at each time point (T1, T2 and T3). Then, prior to evaluating reliability of angular kinematics at discrete time points, analyses of variance (ANOVA) for repeated measures ($p < 0.05$) were performed to detect potential systematic change in angular kinematics over time (Weir, 2005). For variables that did not show systematic change over time, reliability of both measurement systems was calculated using intraclass correlation coefficients (ICC) type 3,1 (Weir, 2005). In order to be consistent with previous reliability investigations of cervical spine kinematics (Bulgheroni et al., 1998; Gelalis et al., 2009; Theobald, Jones, & Williams, 2012; Tousignant-Laflamme, Boutin, Dion, & Vallée, 2013), ICCs were interpreted according to criteria described by Fleiss (1999) (ICC < 0.4 represents poor reliability, 0.4–0.75 fair to good, and > 0.75 excellent). In addition, standard error of the measurement of the true score (SEM), minimal detectable change (MDC) were calculated (Weir, 2005). Results describing reliability at discrete time points (ICC, SEM and MDC) were calculated for all participants, as well for the two sub-groups (players and non-players) separately. Reliability of kinematic curves was evaluated using coefficient of multiple correlation (CMC) (Kadaba et al., 1989) and standard deviation (Curve SD).

Analyses were performed using SPSS (version 22, IBM Corporation, Armonk, NY, USA) (ANOVA, ICC), Microsoft Excel 2010 (Microsoft, Redmond, WA, USA) (SEM, MDC), and MATLAB (CMC, Curve SD).

3. Results

Descriptive statistics are presented in Table 2. All ANOVAs for repeated measures were non-significant ($p = 0.07$ – 0.92).

Overall reliability values at discrete time points ranged between 0.44 and 0.95 for ICCs, and between 1 and 7°, and 3 and 20° for SEM and MDC values, respectively (Table 3). Tables 4 and 5 present ICC, SEM and MDC results for player and non-player participants, respectively.

Standard deviation values of kinematic curves ranged between 2 and 6°, while CMC values ranged between 0.5 and 0.69, with one complex number $0.51 + 0.03i$ (Table 6).

Figure 2 illustrates kinematics from all movement directions in a representative participant.

Table 2. Descriptive statistics (mean ± SD) of cervical spine kinematics [°] for each movement direction (FE, LF and ROT) at each time point (T1, T2 and T3) for both measurement systems (Vicon and Polhemus)

		Vicon	Polhemus
T1	FE	-29 (± 16)	-29 (± 13)
	LF	1 (± 5)	2 (± 7)
	ROT	1 (± 5)	5 (± 6)
T2	FE	-15 (± 16)	-20 (± 13)
	LF	0 (± 8)	1 (± 8)
	ROT	1 (± 2)	2 (± 3)
T3	FE	-5 (± 26)	-8 (± 25)
	LF	2 (± 7)	3 (± 6)
	ROT	1 (± 3)	3 (± 3)

FE: Flexion/extension, LF: Lateral-flexion, ROT: Axial rotation, T1: Beginning of trial, T2: Instant of impact, T3: Sustained push

Table 3. Overall reliability results for discrete time points (T1–T3)

		Vicon			Polhemus		
		ICC (95% CI)	SEM (95% CI)	MDC	ICC (95% CI)	SEM (95% CI)	MDC
T1	FE	0.86 (0.71–0.96)	6 (5–6)	16	0.79 (0.59–0.94)	6 (5–6)	16
	LF	0.88 (0.75–0.97)	2 (1–2)	4	0.90 (0.78–0.97)	2 (1–3)	6
	ROT	0.94 (0.86–0.98)	1 (1–2)	3	0.89 (0.76–0.97)	2 (1–3)	6
T2	FE	0.95 (0.88–0.99)	4 (2–5)	10	0.90 (0.77–0.97)	4 (2–6)	11
	LF	0.90 (0.79–0.97)	3 (1–3)	7	0.86 (0.71–0.96)	3 (2–4)	8
	ROT	0.47 (0.22–0.79)	2 (1–2)	5	0.48 (0.23–0.80)	2 (1–2)	6
T3	FE	0.92 (0.83–0.98)	7 (4–10)	20	0.93 (0.84–0.98)	6 (3–9)	18
	LF	0.88 (0.75–0.97)	2 (1–3)	6	0.84 (0.67–0.95)	2 (1–3)	6
	ROT	0.66 (0.42–0.89)	2 (1–2)	4	0.44 (0.19–0.77)	2 (1–2)	5

ICC (95% CI): Intraclass correlation coefficient (3,1) with 95% confidence intervals, SEM: Standard error of the measurement [°], MDC: Minimal detectable change [°]

FE: Flexion/extension, LF: Lateral-flexion, ROT: Axial rotation
T1: Beginning of trial, T2: Instant of impact, T3: Sustained push

4. Discussion

To help researchers opt for the most appropriate system for measuring cervical spine kinematics during scrums, this study assessed test-retest reliability of an EMT and OMC system during this task.

The overall results suggest that both systems have comparable reliability. In both systems, ICCs were generally considered to be excellent (Fleiss, 1999) with seven out of nine values being >0.75. Moreover, both systems showed fair to good (Fleiss, 1999) reliability values in the same movement directions and at the same time points (i.e. axial rotation at impact and during the sustained push). An examination of the raw data revealed that within- and between-subject variability differed by a smaller amount in lower, compared to higher ICC values. For example, for axial rotation at impact, the ICC value was 0.48 (EMT data), and within- and between-subject variability was 4° and 5°, respectively (i.e. difference of 1°). In contrast, for flexion/extension at impact, the ICC value was 0.90

Table 4. Reliability results for discrete time points (T1-T3) in player participants

		Vicon			Polhemus		
		ICC (95% CI)	SEM (95% CI)	MDC	ICC (95% CI)	SEM (95% CI)	MDC
T1	FE	0.96 (0.94–0.99)	3 (1–3)	8	0.82 (0.50–0.99)	3 (1–3)	7
	LF	0.92 (0.74–0.99)	2 (1–3)	5	0.89 (0.66–0.99)	2 (1–3)	5
	ROT	0.94 (0.81–0.99)	1 (1–2)	3	0.23 (0.03–0.86)	1 (1–2)	3
T2	FE	0.95 (0.81–0.99)	2 (1–4)	7	0.76 (0.40–0.98)	3 (1–3)	8
	LF	0.97 (0.87–0.99)	2 (1–3)	4	0.78 (0.44–0.98)	3 (1–3)	8
	ROT	0.68 (0.30–0.97)	2 (1–2)	4	0.42 (0.07–0.92)	2 (1–2)	6
T3	FE	0.87 (0.60–0.99)	4 (1–5)	10	0.30 (0.00–0.89)	2 (1–3)	7
	LF	0.91 (0.71–0.99)	2 (1–3)	6	0.86 (0.60–0.99)	2 (1–3)	5
	ROT	0.83 (0.53–0.99)	1 (0–2)	4	0.11 (0.08–0.78)	1 (1–2)	2

ICC (95% CI): Intraclass correlation coefficient (3,1) with 95% confidence intervals, SEM: Standard error of the measurement [°], MDC: Minimal detectable change [°]

FE: Flexion/extension, LF: Lateral-flexion, ROT: Axial rotation

T1: Beginning of trial, T2: Instant of impact, T3: Sustained push

Table 5. Reliability results for discrete time points (T1-T3) in non-player participants

		Vicon			Polhemus		
		ICC (95% CI)	SEM (95% CI)	MDC	ICC (95% CI)	SEM (95% CI)	MDC
T1	FE	0.73 (0.41–0.96)	7 (5–8)	19	0.73 (0.42–0.96)	6 (5–7)	17
	LF	0.78 (0.49–0.97)	1 (0–1)	3	0.91 (0.75–0.99)	2 (1–3)	5
	ROT	0.71 (0.38–0.96)	1 (1–2)	3	0.89 (0.70–0.99)	2 (1–3)	6
T2	FE	0.95 (0.85–0.99)	4 (3–4)	10	0.93 (0.79–0.99)	3 (1–5)	9
	LF	0.82 (0.55–0.98)	2 (2–3)	7	0.86 (0.64–0.98)	3 (1–4)	8
	ROT	0.18 (0.04–0.75)	1 (1–2)	3	0.57 (0.22–0.92)	2 (1–2)	6
T3	FE	0.77 (0.47–0.97)	7 (6–8)	20	0.83 (0.58–0.98)	9 (3–12)	26
	LF	0.85 (0.62–0.98)	2 (1–2)	5	0.84 (0.59–0.98)	2 (1–3)	6
	ROT	0.40 (0.09–0.87)	1 (1–2)	3	0.53 (0.19–0.91)	2 (1–2)	4

ICC (95% CI): Intraclass correlation coefficient (3,1) with 95% confidence intervals, SEM: Standard error of the measurement [°], MDC: Minimal detectable change [°]

FE: Flexion/extension, LF: Lateral-flexion, ROT: Axial rotation

T1: Beginning of trial, T2: Instant of impact, T3: Sustained push

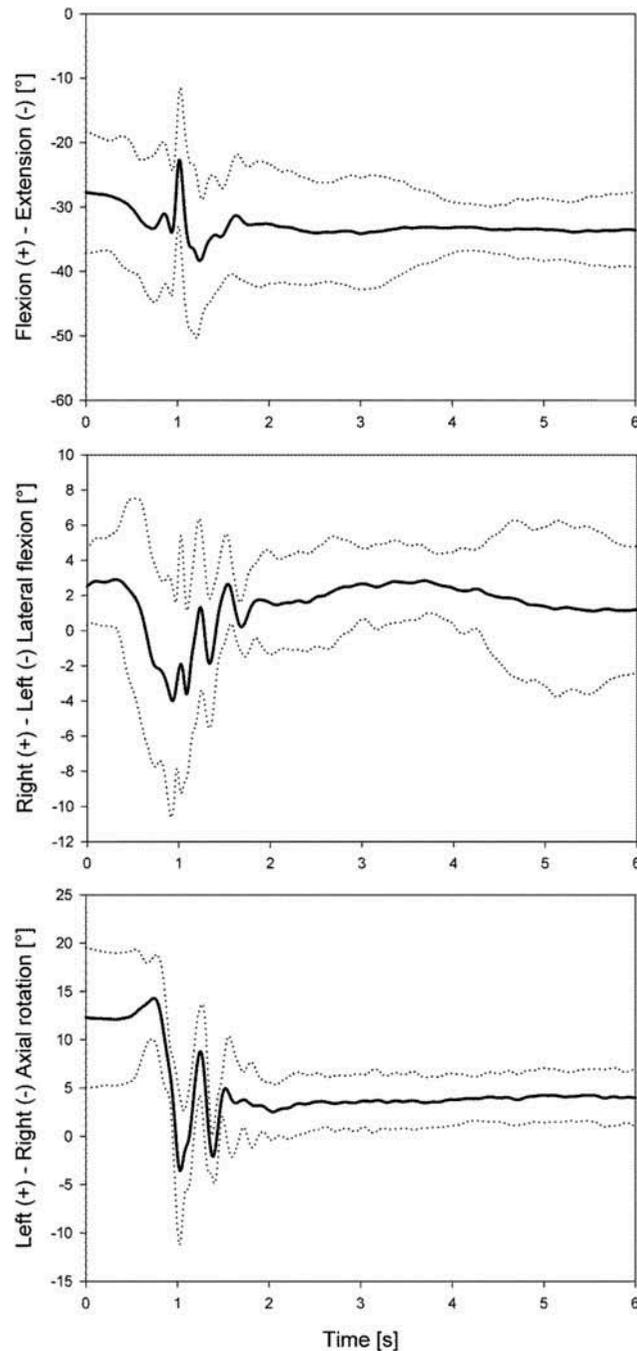
Table 6. Reliability results for kinematic curves

	Vicon		Polhemus	
	CMC	Curve SD	CMC	Curve SD
FE	0.69	6	0.65	6
LF	0.51 + 0.03i	2	0.58	3
ROT	0.50	2	0.58	3

CMC: Coefficient of multiple correlation, Curve SD: Standard deviation of kinematic curves [°]

FE: Flexion/extension, LF: Lateral-flexion, ROT: Axial rotation

Figure 2. Representative curves of one participant's movements in flexion/extension, lateral-flexion, and axial rotation (mean \pm 2 standard deviations).



(EMT data), and within- and between subject variability was 4° and 14° , respectively (i.e. difference of 10°). A small between-subject variability is likely to explain the moderate ICC values, since it is known that ICC values are negatively affected by low between-subject variability (Weir, 2005).

Similarly, CMC calculations are sensitive to factors like the amplitude of movement investigated (Røislien, Skare, Opheim, & Rennie, 2012). Such constraints may explain the moderate values and the complex number obtained in this study.

It should be noted that there is no universal criteria to evaluate relative reliability indices (e.g. ICC and CMC) (Portney & Watkins, 1993) and that qualifiers, such as “excellent” for an ICC value, should be interpreted with caution (Charter & Feldt, 2001; Portney & Watkins, 1993; Weir, 2005). The interpretation should be adapted to the investigated topic and in the light of absolute reliability results, such as SEM and MDC, to put the results into perspective (Weir, 2005).

In relation to SEM and MDC values, both measurement systems appeared again to vary similarly, with consistently lower values for lateral-flexion and axial rotation, and higher values for flexion/extension. This pattern further supports the notion of comparable reliability across both systems. These results suggest that higher values in flexion/extension were due to decreased repeatability in head movement, which was indeed conceivable in this study because a scrum machine does not constrain head movements in extension (Preatoni, Stokes, England, & Trewartha, 2012). In practice, the higher MDC values in flexion/extension indicate that a relatively large change in these values would be required to be confident a true change had occurred. In a contested scrum, however, the head is forced in a flexed position, such that a more consistent movement pattern might be observed in this scrum variation, but this warrants further investigation.

In the present study, only a small sample size has been included ($N = 9$) with participants of heterogeneous abilities. However, the 95% confidence intervals (CI) demonstrated that SEM values were relatively stable with deviations of only 0–3° from mean SEM. Moreover, a comparison of the overall results with the two sub-groups showed that the inclusion of inexperienced participants did not artificially “inflate” ICC values. These results actually revealed that practicing the scrum reduces within-subject movement variability, since most ICC values were higher for experienced players than for non-player participants. This point is further supported by most of the SEM and MDC values, which were substantially lower in players than in non-players. Indeed, SEM and MDC were even lower in players than in non-players when ICC values were low. For example, for ROT at the beginning of the trial, ICC was 0.23 in players as opposed to 0.89 in non-players (EMT data). However, SEM and MDC were only 1° and 3° in players respectively, compared to 2° and 6° in non-players.

There is one limitation associated with the use of EMT for field-based measures. In this study, T1–T4 were identified using the OMC system, but in the field, where it is impossible to have an equivalent system, this task would become more difficult. One possibility, if investigating contested scrums, could be to place sensors on opponents and define the moment of impact as the time point at which the smallest distance between the sensors on both opposed players is first achieved. Nevertheless, the difficulty of identifying specific time points in kinematic measurements is a problem common to every non vision-based measurement system, including inertial measurement units (Swaminathan et al., 2016a).

In conclusion, EMT and OMC systems demonstrated similar reliability, although OMC appeared to provide slightly more reliable results. However, this is in line with previous work (Koivukangas, Katisko, & Koivukangas, 2013; Lugade et al., 2015) and both systems are considered to be adequately reliable to measure cervical spine kinematics during repeated scrums, for example under different conditions or before and after an intervention. Nevertheless, detecting changes in flexion/extension patterns may be difficult when investigating scrums performed against a scrum machine.

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Competing interests

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