Exploring lumbo-pelvic functional behaviour patterns during osteopathic motion tests: a biomechanical (en)active inference approach to movement analysis

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ABSTRACT

Background: Observing how individuals actively adapt to their environment may provide additional insights into traditional clinical tests. Rather than using tests that only identify joint mobility limitations, it seems relevant to use clinical motion tests that assess global biomechanical functions more generally and identify functional behaviours.

Objectives: This study explores whether different functional kinematic behaviour patterns appear when executing a new complex motor task and whether those observations are consistent over multiple executions.

Methods: Marker-based kinematic analyses of the lumbo-pelvic complex were conducted on 29 asymptomatic athletes during two active self-induced motion tests: the one-sided tilt test and a modified version of this test limiting the trunk axial rotation. Marker data served as an input for a full musculoskeletal model to compute the lumbar and lower limb joint angles. Latent class analysis and intraclass correlation coefficients were calculated to identify different classes of functional kinematic behaviour and assess the reliability between measurements.

Results: The methodology allowed us to identify four distinctive classes of possible movement combinations based on these two functional tests: standard movement, low knee and lumbar engagement, high pelvis engagement and high lumbar flexion. All ICCs for the lumbo-pelvic complex degrees of freedom were higher than 0.6, suggesting a moderate to good reliability for the overall test.

Conclusion: It remains unknown whether the observed reproducible patterns emerging from the motion test relate to motivation and prior experiences. Further explorations are required to investigate whether these behaviours can be correlated to empirical clinical observations, past experiences, and future vulnerabilities for musculoskeletal conditions.

Keywords: One-sided tilt test, biomechanical analysis, lumbar mobility, motion tests, lumbo-pelvic complex.

1. Introduction

Non-specific low back pain is characterised by symptoms without clear causes, with an unknown origin, and is the most prevalent form of low back pain [1,2]. Among all the factors involved in non-specific low back pain (e.g. psychological, social, biological, training, etc.) [3–5], the potential involvement of musculoskeletal factors remains unclear [6–8].

In the field of osteopathy, positional and joint motion tests are widely used [9–13] even if controversies remain on their relevance compared to pain provocation tests [14]. When exploring the motion of the lumbo-pelvic complex, tests such as the standing flexion test, sacral springing, the Stork/Gillet test and the one-sided tilt test (hip drop test) are commonly used in manual assessment [15–18]. They were developed to help practitioners analyse and evaluate the structural and functional integrity of the body in line with the critical reasoning of osteopathic principles [19]. However, their lack of reliability and validity questions have challenged their true contribution to the clinical decision process [14,20,21].

A large debate still persists about their use in research/education and beyond models and theoretical frameworks for manual care [22–24]. Judging the specific and functional tests commonly practised in a clinical context depends primarily on subjective analyses made by the clinician and based on training, experience and personal feelings [25]. Choosing and interpreting correctly functional/manual tests lies in identifying joint dysfunctions, the existence of which remains difficult to detect [26]. This does not necessarily raise doubts about the effectiveness or efficiency of manual care in general, but the literature on the issue questions the assessment methods used [27–30].

While manual tests often focus on the biomechanical function of a specific joint, the overall behavioural manifestations (i.e. global movement) have put into light the intricate relationship of a whole chain of interlinked subcomponents [29,31] and are associated with higher levels of inter- and intra-operator reliability [32,33]. Exploring global movement during traditional clinical tests could reveal the important role they might play in osteopathic practice.

Functional movement disorders have been shown to be closely related to alterations in motor control, reduced discriminatory sensation, catastrophising, fear avoidance and loss of self-confidence [34,35]. Therefore, motion tests might be useful to understand different strategies or functional behaviours used by the patient during complex motor functions and thus develop a better understanding of what the patient is feeling or any avoidance pattern during movement as well as potential opportunities to change/adjust them [29,36]. The 'embodied self' [37] partly defines our decision-making, actions and interactions with the external world and is a central part of enaction [38,39]. Hence, a global appreciation of motion tests might be useful to understand the different strategies or functional behaviours used by a patient during complex movements [34,35]. Beyond pain avoidance, functional traits could also emerge in asymptomatic individuals.

This new approach to clinical interpretation emphasises the patients' ability to engage with their environment [40]. It provides insights into the way patients perceive their environment and act accordingly, particularly how they adjust to their environment by acting upon or changing the world predicted by their generative model, i.e., through active inference [40,41]. Active inference enables us to understand sentient behaviour-perception, planning, and action in terms of probabilistic inference [42]. The emphasis is on patient perception and enactment rather than on the practitioner's ability to detect somatic abnormalities [40,43].

Current methods in biomechanics are increasingly advancing to analyse the human movement in three-dimensions (3D) based on marker-based motion capture systems [44–47]. Therefore, these methods could explore the functional behavioural traits revealed during motion tests [48,49].

The first step to support such a hypothesis is to document whether different functional kinematic behaviour patterns appear when executing a new complex motor task and whether those observations are consistent over multiple executions.

2. Materials and Methods

2.1. Study Design

An observational design protocol based on repeated-measures was set up to evaluate (1) individual functional behaviours and (2) intra-rater and inter-rater reliability over multiple executions of two functional lumbo-pelvic tests. This study was designed by the Institut d'Ostéopathie de Rennes - Bretagne in collaboration (#2018-277) with the Movement, Sport and health Sciences laboratory (M2S). The protocol was approved by the Research Committee of the Institut d'Ostéopathie de Rennes - Bretagne in September 2019 and met the requirements of the Declaration of Helsinki.

2.2. Participants

No sample size calculation was undertaken. A convenience sample of 29 asymptomatic athletes (males/females: 13/16; age: 25.8 +/- 6.1 years) was constituted in combination with the research projects being conducted in the laboratory at the time of the study. All athletes were informed prior to participation and completed a consent form granting their approval to this experimental setup.

2.3. Full-body movement analysis

A 24-camera motion analysis system (Qualisys AB, Göteborg, Sweden) was used to gather the kinematic data. A global Cartesian coordinate system was oriented in such a way that the X-axis was antero-posterior, pointing anteriorly, while the Y-axis was medio-lateral pointing to the participant's left and the Z-axis was vertical from bottom to top. The acquisition frequency was 200 Hz.

The participants were equipped with 47 retroreflective markers attached to the skin over pre-selected anatomical landmarks using medical tape in accordance with previous similar studies [50,51] as shown in Figure 1. All landmarks were located and marked through manual palpation from a final-year osteopathy student and verified by a second senior investigator.

This procedure is used routinely in biomechanics to evaluate movement in accordance with the requirements of the International Society of Biomechanics [52,53].

**** Insert Figure 1 about here ****

2.4. Active movements

Two active self-induced movements were performed by the athletes to obtain the ROMs of the low back when tilting the pelvis to the right and to the left side.

The first movement, the one-sided tilt test (cOST), also known as the "Hip drop test" or "Gossip test", is an active voluntary movement used by practitioners to analyse the one-sided range of lumbar motion on the right and left sides starting from a static position used in a clinical setting for individuals with nonspecific back pain [15,54]. The interpretation of this test is based on the subjective observation of how well the lumbar spine compensates for sacral base declination. The clinical interpretation of this test performed on the tested side and on the opposite side in several regions simultaneously (lumbar, pelvis, hip and knee) explored the overall individual functional behaviours of the participant during this task. The second movement was a modified one-sided tilt (mOST), to limit the pelvic rotation, keeping the pelvis in the frontal plane to keep the movement focused on the lumbo-sacral region. All the instructions provided for these two tests are presented in Table 1.

**** Insert Table 1 about here ****

2.5. Experimental protocol

Both active movement tests were explained and shown to the athletes several times before recording. Initially, the athletes stood in an anatomical position. After recording a static calibration step, the athletes were verbally instructed to perform three attempts of the cOST on each side (right and left) as previously described in Chenaut et al., (2019). To do this, each participant had to bend one knee allowing the pelvis to tilt towards the same side. Then, they performed three mOST trials on each side (right and left). The trial duration was not controlled in order for the participants to move at a comfortable speed. The athletes were asked to limit the pelvis rotation to favour the side-bending of the pelvis on the same side as the bent knee (Table 1). Finally, six trials of each test were recorded for each athlete.

2.6. Outcomes and data analysis

Motion capture data were pre-processed using the QTM software (Qualisys AB, Göteborg, Sweden), involving marker labelling, gap filling and its export to a c3d file. A full-body musculoskeletal model, developed by Raabe & Chaudhari, (2016) was used to compute sacro-lumbar, pelvis and knee joint angles [47,48] according to the recommended OpenSim calculation steps [56] (Figure 2).

*** *Insert Figure 2 about here* ***

The model was scaled to match the participants' anthropometry using anatomical landmarks (segment lengths). A joint angle calculation was performed with OpenSim 3.3 using a global optimisation-based inverse kinematics procedure [56].

A postprocessing was finally conducted through a custom-built MATLAB routine (R2019a, MathWorks, Inc, Natick, MA, USA). The three degrees of freedom (DOF) of the sacro-lumbar joint (flexion/extension, side bending and rotation) and of the pelvis (flexion/extension, side bending and rotation) were assessed at the peak of the right knee flexion (right-hand side) and for the left knee flexion (left-hand side) previously identified during each test.

2.7. Statistical Analysis

The pelvic and lower limb ranges of motion for each participant, during each of the three executions, on each side, were imported into the Stata statistical software (*Release 15*. College Station, TX, USA: StataCorp LLC). The data quality was verified by listing outliers with results beyond the possible ranges of motion. Once an outlier was detected, the information was backtracked to the original data to identify and correct caption errors. The final dataset was sealed for full analysis. If functional behaviour is symmetrical, data from both sides can be associated. To test this assumption, a generalised random-effects least-square regression confirmed that the ranges of motion did not differ for all 14 measured variables between the left and right sides. The results from the tests related to the left hemi-pelvis were transformed (i.e. positive or negative value) to report the ranges of motion as if they had been measured on the right side. All analyses were therefore done at the hemi-pelvis level to account for the lack of independence between measures from the same participants. The consistency of the measure over time when repeating the cOST and the mOST was also tested using a generalised random-effects least-square regression. A descriptive analysis was done to measure the standard values for the range of motion for each test to test the assumption of normality and to compare the ROM between cOST and mOST.

Using the first trial of each on its own, latent class analysis was then performed to identify different classes of movement combinations. Fourteen variables were used to model classes (seven from each test). The optimal number of classes was defined by choosing the number of classes before the Bayesian Information Criterion (BIC) increased with additional classes. To ensure the reliability of the process, a one-way random-effects model with absolute agreement was used to measure the intra-class correlations (ICC) between each of the three measures of ROM. The significance level was not corrected for multiple testing and was set at $p < 0.05$. We considered an ICC under than 0.5 to be poor, between 0.50 and 0.75 to be moderate, between 0.75 and 0.90 to be good and over 0.90 to be excellent [57].

3. Results

3.1. Recruitment and subject characteristics

All participants performed the test on both sides. 342 attempts were analysed over eight degrees of freedom in four joints (3 DOF sacro-lumbar, 3 DOF pelvis and 2 DOF ipsilateral and contralateral knee). One participant had to be excluded from the analysis, resulting in a sample size of 29 asymptomatic athletes (males/females: 12/17; age: 25.8 +/- 6.1, mass: 72.0 +/- 9.2 kg; height: 175.5 +/- 8.7 cm; body mass index: 23.4 +/- 2.5 kg/m^2). The reasons for their exclusion were technical issues that led to the loss of the kinematic data (missing markers). Once any asymmetries and lack of independence from measures of DOFs from both sides were ruled out, the data collected on the left side was able to be transformed by transposition to represent their mirror image making them comparable to those assessed on the right side. Three conditions for the achievement of the two tests were proposed: (1) the ipsilateral side-bending of the pelvis had to be greater than 0°, (2) the ipsilateral knee had to be bent into an angle superior to 15° while (3) the contralateral knee had to be bent into an angle inferior to 20° which resulted into a posture where the ipsilateral knee was flexed more strongly than the contralateral one.

3.2 Normative data and comparison of the observed range of motion between the two tests

An opposed kinematic was observed between the pelvis (anterior tilt, ipsilateral side-bending, contralateral rotation) and the sacro-lumbar joint (extension, contralateral side-bending, ipsilateral rotation) during the two functional tests.

Compared to the classic test, the modified test limited pelvic rotation (accordingly 21.8 ± 5.5° to 1.8 ± 6.2°; mean ± SD) and knee flexion (accordingly 48.2 ± 5.7° and 36.5 ± 6.7°). Additionally, other kinematic differences were observed between the two tests for the pelvis ROM; a decrease of flexion and side bending ROM between the mOST test versus the OST test with respectively 15.9 ± 12.8° vs 2.0 ± 1.8° and 27.2 ± 6.3° vs 14.0 ± 4.0°. The results also showed in the mOST test a decrease in side bending and rotation ROM for the lumbar joint (respectively 21.8 ± 5.5° vs 14.2 ± 4.0° and 11.2 ± 13.7° and 0.8 ± 7.8°) when compared to the OST test. However, a similar ROM was found between cOST and mOST for the lumbar flexion/extension (0.5 ± 7.8° and 0.4 ± 1.5°, respectively).

3.3 Observed classes of functional behaviour

Fifty-eight hemi-pelvis were analysed using fourteen parameters from the two functional tests. Using BIC, the best fit was observed with five classes. The four remaining most common classes are illustrated in Figure 4 and all degrees of freedom of the sacro-lumbar, pelvis and knee joints were reported in Table 3. A sensitivity analysis was also undertaken to analyse cOST and mOST separately. When assessing both functional tests separately, BIC identified four classes for each test, corresponding to 16 potential different patterns. The model including all 14 parameters and five classes appeared to be the most relevant and was thus the one retained (Table 2).

**** Insert Table 2 about here ****

**** Insert Figure 3 A, B, C, D about here ****

The 'Standard Movement' class (Figure 3A)

This class corresponds to the expected motion behaviour (related to the description of the requested task) for both the cOST and the mOST.

Twenty hemi-pelvis belonging to 14 participants were classified into this category. All eight participants who had their hemi-pelvis classified into two different classes, had one element belonging to this class. This class was therefore used as a baseline for comparison with the other classes.

The ‘*Low knee and lumbar engagement*’ *class* (Figure 3B)

This class differs from the Standard Movement class by showing a reduced ROM for all seven studied DOF. This class includes twenty-one hemi-pelvis belonging to 11 participants. It is essentially characterised by a combined reduction in the bending range of motion of the ipsilateral knee and the contralateral lumbar side.

The ‘*High pelvis Engagement*’ *class* (Figure 3C)

Within this class, we observed a significant increase in the maximum pelvic ROM in relation to forward tilt and contralateral rotation associated with a decrease in the lumbar contralateral rotation. This class included seven hemi-pelvis belonging to five participants. For the mOST, the behaviour was very similar to *the Standard Movement class* with a slight decrease in ipsilateral knee engagement impacting all the maximum joint amplitudes. Note that in the mOST, the participant is asked to limit pelvic rotation as much as possible while keeping his pelvis in the frontal plane.

The ‘*High Lumbar Flexion” class* (Figure 3D)

The results showed a similar behaviour between the two performed tests and were characterised by an increase of lumbar flexion associated with a decrease in ipsilateral pelvic anterior tilt and an increase in contralateral pelvic rotation when compared to the standard class. This class included eight hemi-pelvis belonging to five participants.

An additional class was identified to which a single individual belonged. We observed an increase in all DOF characterised by an atypical behaviour during the two active self-induced motions.

3.4 Reliability of the measures

The reliability of the joint angle measures during the two tests was ascertained over the 342 trials recorded. A good reliability of single measures (ICC ranging from 0.76 to 0.92) was observed for all degrees of freedom measured during the OST test. To be more precise, the repeated measurements showed good reliability for the one-sided tilt test (from ICC = 0.76 [95% CI 0.67 to 0.84] for the ipsilateral knee flexion to ICC = 0.92 [95% CI 0.87 - 0.95] for the lumbar side bending). The reliability of the mOST test was lower (from ICC =0.40 to 0.84). Repeated measurements showed the lower ICC=0.40 [95% 0.23 to 0.56] for the contralateral knee extension and the higher ICC=0.89 [95% CI 0.84 - 0.93] for the pelvic rotation. All ICC for the pelvis and the lumbar degree of freedom were higher than 0.6 which is an indicator of moderate to good reliability. All intraclass correlation coefficients for each degree of freedom and for the two tests are reported in Table 3.

**** Insert Table 3 about here ****

4. Discussion

4.1. Brief overview of results

This study investigated whether distinct functional behaviours appear when imitating a new complex motor task and whether this behaviour is repeated over multiple executions. Our results showed that a pattern recognition could be achieved by combining the parameters from different tests; the classic (cOST) and modified (mOST) one-sided tilt test. The results also suggested that we can classify low back function in separate classes for use in the clinical setting (ICCs>0.6).

The number of DOF involved during these two functional motions offered a large number of possible combinations of movements and illustrated how complex it is to analyse the motion of the lumbo-pelvic complex in dynamics. By removing a degree of freedom of movement (in axial rotation), the objective was to constrain the athlete into finding another strategy to achieve the requested movement. Our results support the hypothesis that challenging participants in a new experience/movement could reveal different functional patterns. Other than the expected pattern, three other frequent patterns were observed. These patterns seem to reduce the distribution of movement to all possible joint degrees of freedom that could be engaged. However, little is known about why such alternative patterns are adopted and how they can inform clinical decisions.

4.2. Strengths and limitations

This objective approach of measuring active motion tests without physical limitations on a population with high needs in lumbo-pelvic motion could help to understand musculoskeletal strategies and kinematic adaptations linked to mechanical over-or underload of specific joints. Therefore, collecting biomechanical parameters also helps to propose clinical and data-driven hypotheses and may have a high potential in transferring knowledge to practice.

All repeated successive measures were collected in the asymptomatic population. It is not known whether those movements remain reliable in the longer term, or if the study assesses the impact of pain on ROM during these active motion tests (limited external validity for patients with pain). Error detection was efficient for outliers but could have also occurred for measures within the accepted boundaries. Therefore, we cannot exclude that the random noise reduced its accuracy for a more precise classification.

Any relation between pain or kinesiophobia - for example - and the deviation observed from the instructed movement remains unclear. This issue was also observed in other studies investigating potential causes of motion patterns (impaired proprioception, fear-avoidance, habits, etc.) and addressing inverse causality with pain [34,35]. In addition, the method identifies common patterns but misses highly specific and potentially relevant ones (internal validity in detecting all possible patterns for example). Furthermore, some patterns could be linked to the method of measurement (marker's placement, asymptomatic structural bone deformations or degenerations and soft tissue artefact) rather than what could be observed by a clinician.

4.3. Comparison of results to the existing literature

Several studies have already investigated the reliability of existing tests of the lumbopelvic femoral complex with questionable clinical value [14,58–60]. Most of the tests used in daily clinical practice to assess the mobility of this area do not present acceptable reliability levels, with the exception of pain provocation tests [60–63]. However, a recent review on the motion analysis of the lumbar region showed this type of assessment to be reliable [64]. Many professional practices (physical medicine, rehabilitation, ergonomics, etc.) have therefore manifested an interest in motion analysis when it comes to identifying normal/abnormal patterns or parameters should be used to guide diagnosis and treatment [7,44,50,65,66]. Previous studies have highlighted the need for research on changes in lumbar movement patterns, such as the potential mechanisms underlying the persistence of low back pain [47,67–69]. In sports sciences, particularly, applied biomechanics tends to investigate and analyse skilled athletes' motions to obtain insights aiming to improve sports techniques, design effective training methods, classify athletes' techniques and prevent injuries [70–72]. However, it still remains difficult to identify relevant methodologies and biomechanical parameters to assess low back function [6,8].

Two previous studies have established the first normative values of the cOST [73,74] and identified two distinct patterns of pelvic motion in forward tilt (most common) or posterior tilt during cOST in fourteen female participants. Moreover, the opposed kinematics between the pelvis (ipsilateral side-bending, contralateral rotation) and the sacro-lumbar joint (contralateral side-bending, ipsilateral rotation) shown in our results were previously observed during the cOST test in twenty-two asymptomatic athletes [48]. However, only one test was used, and the standardisation of the procedure was not done as precisely as in the current study. Combining results from more than one functional test seems to improve interpretability as shown in previous studies [63,75,76]. Even if the recognition of movement patterns can have a clinical value, no studies have yet been able to answer whether any specific pattern could be optimal for a given function (e.g. sports activity), or if those patterns are a personal adaptation made in order to optimise function. Further studies are needed to link these results to the characteristics, performances or symptomatology in athletes.

4.4. Practical applications

The three-dimensional (3D) kinematic analysis of the lumbo-pelvic complex enable us to isolate and describe four major athletes' profiles of motion occurring during these functional tests. Therefore, the methodology proposed in this study could open new perspectives on how to use such patterns in clinical reasoning when screening for a specific functional behaviour. Our results highlighted the variety of functional patterns found in asymptomatic athletes that could have important implications for healthcare orientations.

The observed results may help solve the somatic dysfunction conundrum [26]. Rather than using tests aimed solely at identifying joint mobility limitations, the idea is to 'take a step back' and use tests that assess biomechanical function more broadly and identify functional behaviours, allowing a personalised approach to the overall active motion [29,36]. Therefore, avoiding to restrict observation and movement analysis to a single joint could lead to more reliable results [29]. This approach is close to a certain concept of "*bony segments as mobile units within a mobile system"* [29] that highlighted the importance of interpreting the local motion of body parts by using gross motion tests within a broader functional system. Collecting more descriptive and tangible evidence of asymptomatic individual motor behaviours not limited to a traditional structural model of articular dysfunction could help provide a plausible model to explain the underlying possible mechanism of manual therapy by attempting to link osteopathic dysfunctions to motor control and (en)active inference.

Any models, however, remains an interpretation of reality and inevitably simplistic compared to the overall complexity of human motion. The most relevant models are therefore the ones that are able to correctly predict outcomes and both based on one's clinical experience and empirical research. Emerging evidence supports the idea that functional motion disorders can be associated with disturbances in one's body perception and embodiment process. These are maybe closely linked to the alteration of motor control, reduced discriminatory sensations, catastrophising, fear-avoidance, losses of self-confidence and affective responses to anticipated pain-related outcomes [77]. Therefore, associating manual care to an analysis of human motion could be an interesting perspective to explore the influence of interoception and active inference on the ROMs. Hence, this approach could provide feedback to the patient on the movement he performed and induce subconscious motor adaptations (influencing physiology and motor behaviour) in order to enhance the perception of pain improvements. This is of major importance for education and research in manual therapy healthcare.

Patients' perceptions and their associated generative model could also be challenging to understand and to take into consideration on a therapeutic level. However, working with patients to improve knowledge about their pain during active motion, recontextualise their sensory feedback and alter their generative model is also an interesting perspective in osteopathic care suggested by several authors [40,78–80].

Identifying and better understanding the most common patterns of motion behaviours found in athletes in response to active motion tests could (1) contribute to the creation of a database allowing the comparison of a larger cohort and (2) address the future challenge of studying how pain/functional discomfort influences motor behaviour according to the performance of these functional tests. Future studies with a larger cohort including symptomatic and asymptomatic athletes, as well as a comparison with clinical history and data, may be a potential orientation to optimise the follow-up of athletes. Introducing patient feedback on perception and potential effects on changes in movement behaviour to establish a cohort observation of the links between existing patterns and future injury or discomfort could be an interesting perspective. Additional determinants could be explored during active motion tests both with additional instrumental approaches (electromyography, external forces) and non-instrumental approaches (self-reported - perceived pain, stress levels and impact on daily life). In this sense, simplifying the procedures used to collect and summarise 3D motion analysis (open-access database) while investigating the validity of pattern recognition using clinical observation for practitioners could be useful to engage researchers and clinicians into the same project of exploring the clinical interpretation of active motion tests that could be an excellent opportunity for the profession.

5. Conclusion

Biomechanical analysis is an interesting perspective to identify "nuances" during the execution of active motion tests used in osteopathy and a support for clinical investigation in order to collect tangible data on human behaviour. The results support the idea that healthy individuals have different standard patterns when it comes to execute unknown motor tasks. The combination of the two proposed tests provides new clinical insight into the lumbo-pelvic motion and reveals how the process in itself could improve interpretability. Whether the observed reproducible patterns emerging from the motion test relate to motivation and prior experiences remains unknown. The osteopathic profession would benefit from knowing to what extent this might play a role in changing motor behaviour and (en)active inference and consequently have an impact on symptoms or performances in real-life activities. Further explorations are therefore required to investigate whether these behaviours correlate with empirical clinical observations, past experiences, performance, and future vulnerabilities in relation to musculoskeletal conditions.

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Tables

Table 1. Starting postures and instructions given to the athletes to evaluate lumbo-pelvic motion evaluation with the two functional tests (cOST and mOST).

Table 2. Range of motion in degrees (mean, CI95% sup and CI95% inf) calculated for each class identified during the two tests, one-sided tilt test (cOST test) and modified one-sided tilt test (mOST test) at the peak of ipsilateral knee flexion.

Table 3. Intraclass correlation coefficients for each degree of freedom of the lumbo-pelvic complex for the two tests: cOST test and mOST test.

Figures captions

Figure 1. Illustration of the marker set used in this study

Figure 2. Schematic of the musculoskeletal model used. Joint references (A) of the sacro-lumbar, pelvis and knee joints. Three different model views (B) in static, and right and left side.

Figure 3. Radar plot of estimated joint angles during the cOST test (grey) and the mOST test (yellow) at the peak of ipsilateral knee flexion (on the side of the test performed). The three degrees of freedom (3 DOF) of the sacro-lumbar joint (flexion/extension, lateral flexion and rotation), the pelvis (flexion/extension, lateral flexion and rotation) and the ipsilateral knee flexion are presented in the plot. 4 classes of movement were determined (A) Standard movement, (B) Low knee and lumbar engagement, (C)High pelvis engagement and (D) high lumbar flexion. * *For graphical purposes, signs for knee flexion/extension, pelvic tilt, lumbar side bending and lumbar rotation were inversed to be positive.*

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Tables

Table 1. Starting postures and instructions given to the athletes to evaluate lumbo-pelvic motion evaluation with the two functional tests (cOST and mOST).

Active motion Tests	Starting posture	Test instructions
cOST	standing in an anatomical position	To bend one knee allowing the pelvis to tilt to the same side Three trials on each side (right and left) Back to starting posture between each execution
mOST	standing in an anatomical position	To bend one knee allowing the pelvis to tilt to the same side To limit the rotation of the pelvis in order to favour the side-bending of the pelvis on the side of the bent knee Three trials on each side (right and left) Back to starting posture between each test

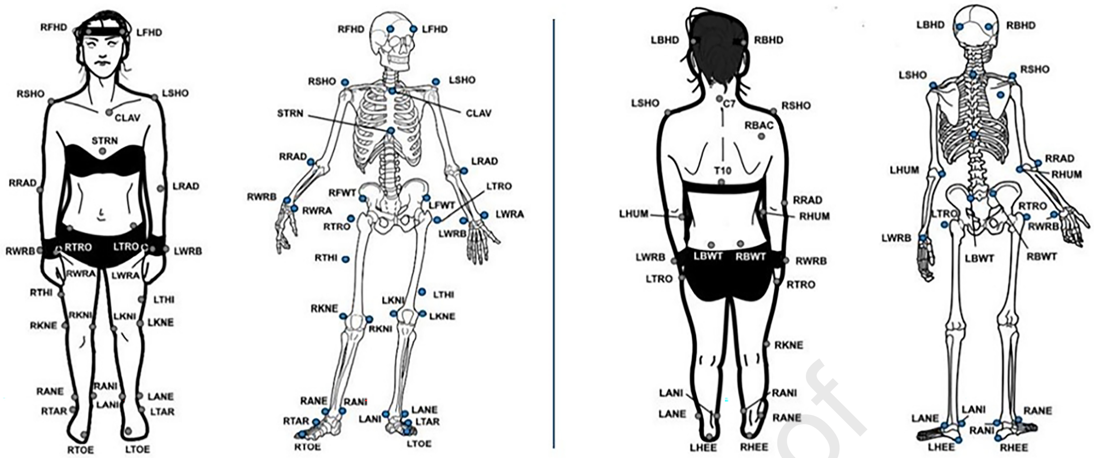
Table 2. Range of motion in degrees (mean, CI95% sup and CI95% inf) calculated for each class identified during the two tests, one-sided tilt test (cOST test) and modified one-sided tilt test (mOST test) at the peak of ipsilateral knee flexion (n=29).

		cOST				mOST			
	Degree of freedom (°)	**Mean (°)**	**Std (°)**	**CI95%sup**	**CI95%inf**	**Mean (°)**	**Std (°)**	**CI95%sup**	**CI95%inf**
Standard movement	Knee flexion	-49.9	1.6	-53.0	-46.8	-40.3	1.9	-44.0	-36.7
	Pelvis ipsilateral side-bending	33.2	1.9	29.5	36.8	13.6	1.0	11.6	15.6
	Pelvis anterior tilt	-12.7	1.4	-15.5	-9.9	0.0	0.5	-1.0	0.9
	Pelvis contralateral rotation	10.0	2.3	5.5	14.4	-3.6	1.2	-6.0	-1.2
	Lumbar contralateral side-bending	-26.0	1.4	-28.8	-23.2	-15.5	1.2	-17.7	-13.2
	Lumbar extension	2.8	1.4	0.2	5.5	0.2	0.6	-1.0	1.5
	Lumbar contralateral rotation	-1.0	3.1	-7.1	5.1	3.8	2.1	-0.3	8.0
Reduced knee and lumbar engagement	Knee flexion	-40.1	1.6	-43.4	-36.9	-28.5	2.0	-32.4	-24.7
	Pelvis ipsilateral side-bending	19.4	1.7	16.0	22.8	9.3	1.1	7.2	11.4
	Pelvis anterior tilt	-6.2	1.4	-8.9	-3.4	-1.1	0.5	-2.1	-0.1
	Pelvis contralateral rotation	4.6	2.2	0.2	9.0	0.9	1.2	-1.5	3.4
	Lumbar contralateral side-bending	-13.7	1.4	-16.4	-11.0	-8.4	1.2	-10.8	-6.0
	Lumbar extension	-2.9	1.4	-5.6	-0.2	-0.8	0.6	-2.1	0.5
	Lumbar contralateral rotation	-3.6	3.1	-9.7	2.5	-1.7	2.1	-5.9	2.5
Hip pelvis engagement	Knee flexion	-49.1	2.7	-54.3	-43.8	-33.6	3.2	-39.8	-27.4
	Pelvis ipsilateral side-bending	31.4	2.9	25.7	37.2	14.3	1.8	10.9	17.7
	Pelvis anterior tilt	-34.7	2.3	-39.3	-30.1	-2.4	0.9	-4.0	-0.7
	Pelvis contralateral rotation	41.4	3.8	34.1	48.8	-0.8	2.0	-4.8	3.1
	Lumbar contralateral side-bending	-23.6	2.3	-28.1	-19.1	-15.3	2.0	-19.2	-11.4
	Lumbar extension	10.0	2.3	5.6	14.5	2.6	1.1	0.4	4.7
	Lumbar contralateral rotation	-31.2	5.2	-41.5	-20.9	6.1	3.6	-1.0	13.2
Lumbar flexion	Knee flexion	-53.6	2.5	-58.5	-48.7	-43.6	3.0	-49.4	-37.7
	Pelvis ipsilateral side-bending	24.8	2.7	19.4	30.2	19.0	1.6	15.8	22.2
	Pelvis anterior tilt	-9.9	2.2	-14.1	-5.7	-4.3	0.8	-5.9	-2.8
	Pelvis contralateral rotation	27.7	3.5	20.9	34.6	10.6	1.9	6.9	14.3

Lumbar contralateral side-bending	-24.0	2.2	-28.2	-19.7	-17.6	1.9	-21.2	-13.9
Lumbar extension	-8.0	2.1	-12.3	-3.8	-0.6	1.0	-2.6	1.5
Lumbar contralateral rotation	-9.1	5.0	-18.8	0.6	-11.5	3.4	-18.1	-4.9

Table 3. Intraclass correlation coefficients for each degree of freedom of the lumbo-pelvic complex for the two tests. cOST test and mOST test.

Degree of freedom	**cOST**		**mOST**	
	ICC	[95% CI]	ICC	[95% CI]
Knee flexion	0.76	[0.67 to 0.84]	0.71	[0.59 to 0.81]
Pelvis ipsilateral side-bending	0.90	[0.86 to 0.94]	0.72	[0.60 to 0.81]
Pelvis anterior tilt	0.90	[0.85 to 0.94]	0.78	[0.68 to 0.86]
Pelvis contralateral rotation	0.92	[0.88 to 0.95]	0.89	[0.84 to 0.93]
Lumbar contralateral side-bending	0.92	[0.87 to 0.95]	0.77	[0.66 to 0.85]
Lumbar extension	0.89	[0.84 to 0.93]	0.61	[0.46 to 0.73]
Lumbar contralateral rotation	0.82	[0.74 to 0.88]	0.85	[0.77 to 0.90]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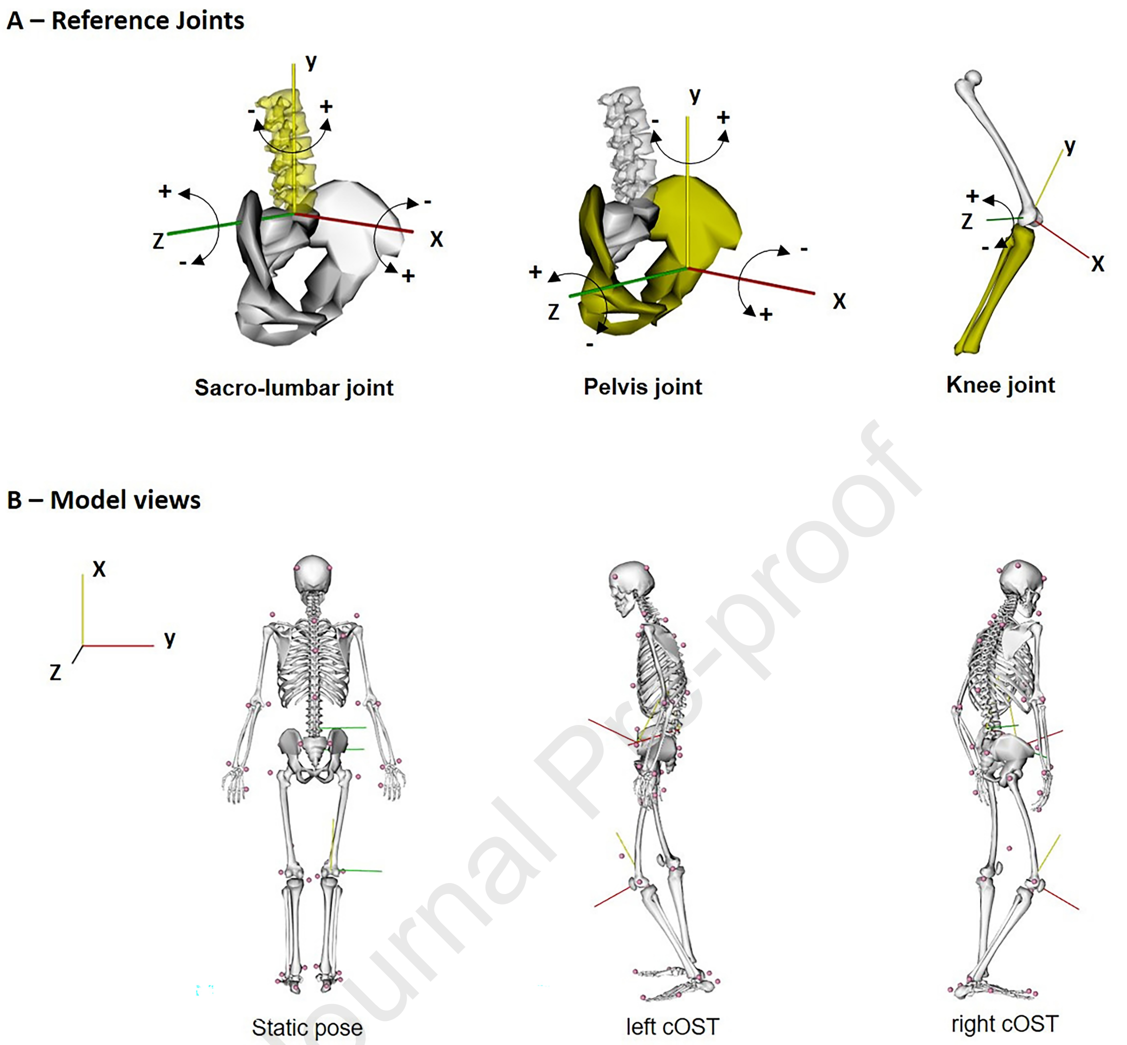
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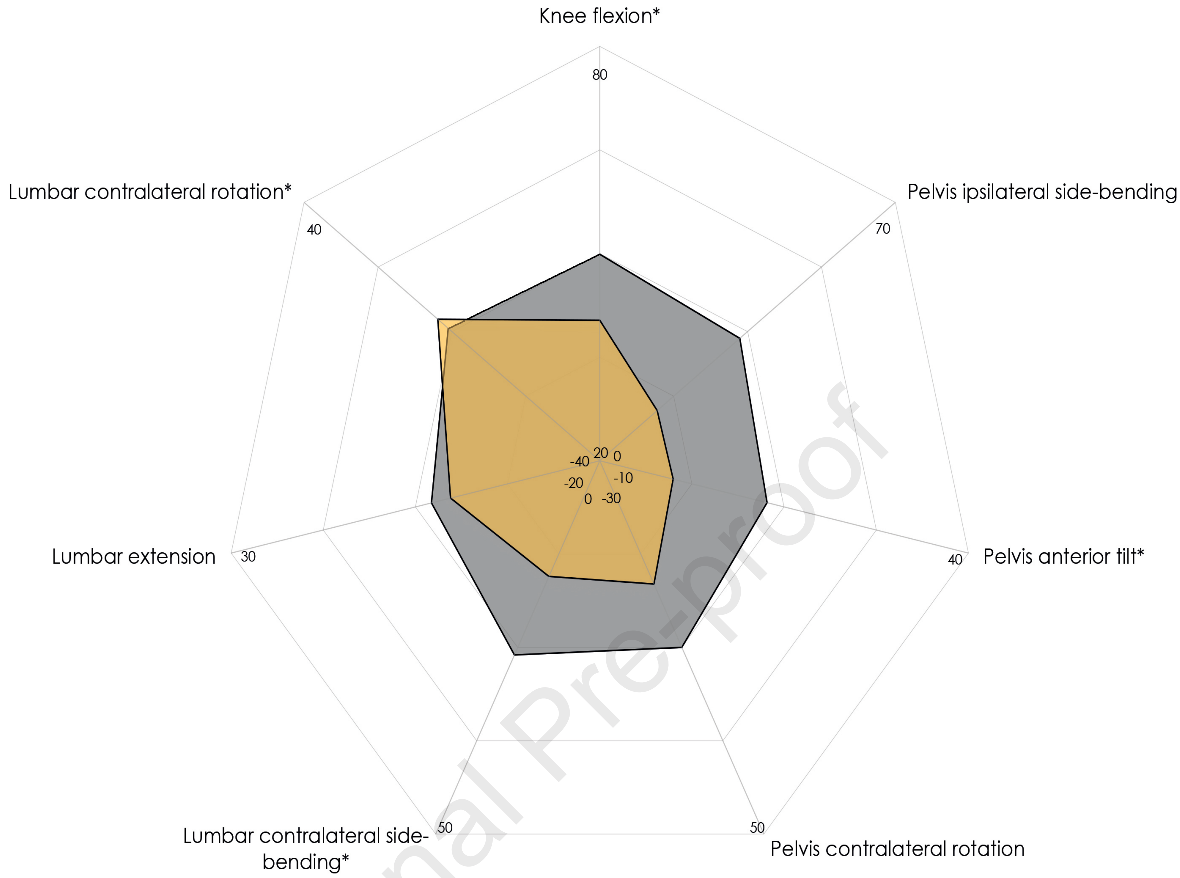

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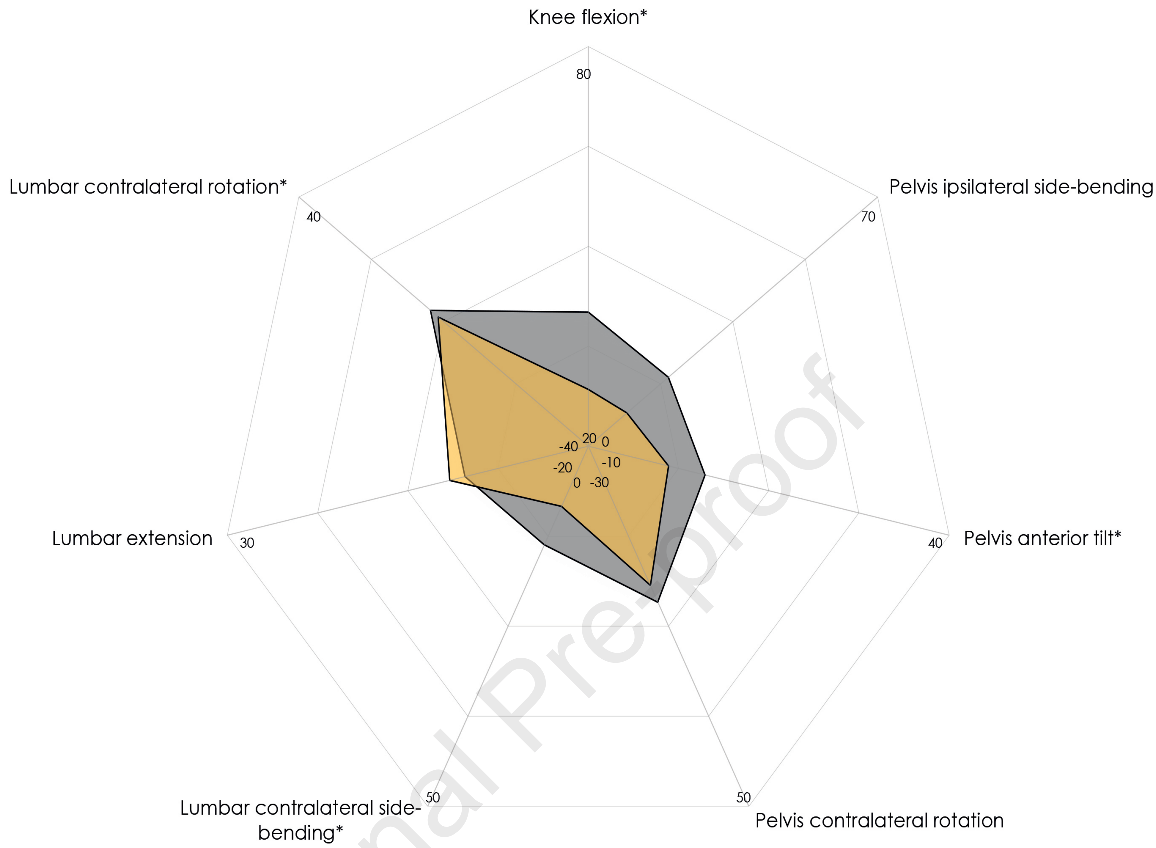

High pelvis engagement

High Lumbar Flexion

Declaration of interests

☐ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☒The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

JE is an associate editor at IJOM. However, he had no role in the processing or decision making with respect to this manuscript.

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