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The use of an electrogoniometer to assess both lumbar range of movement and its conscious control: a comparison between healthy subjects and elite swimmers

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ABSTRACT

BACKGROUND: Lumbar range of movement (ROM) and its conscious control play a crucial role in maintaining lumbar health and result in better limb efficiency, core control, stability and balance. However, there is no single test that assesses both lumbar ROM and conscious control or proprioception. Here, we design a novel test to assess simultaneously lumbar ROM and proprioception (the R&P-t) to determine the reliability of the test, and to compare these outcomes between healthy active students and elite swimmers in order to describe a third outcome: The Relative Error (REr).

METHODS: A total of 34 healthy elite swimmers (mean age: 20.3±4.1 years) and 27 healthy physically active students (mean age: 22.8±2.9 years) volunteered to participate in the study. The participants were blindfolded to obtain the Absolute Error (AEr) and lumbar ROM scores after 3 trials of maximal lumbar flexion, extension and mid perceived position obtained on two different dates separated by 2–3 days.

RESULTS: Intraclass correlation coefficients ranged from 0.89–0.99 for all of the measurements. Lumbar ROM and AEr scores were higher for the active students than the elite swimmers (44.9±13.3° *vs*. 34.4±17.4° and 3.7±9.0° *vs*. 2.4±7.8°, respectively). REr was higher for elite swimmers (32.7±10.0% *vs*. 18.0±2.2%).

CONCLUSIONS: The R&P-t is the first reliable test to assess both lumbar proprioception and ROM with the same equipment. A higher AEr in a reduced ROM implies higher relative joint instability, and the same AEr in a higher ROM corresponds to more relative control over this joint.

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KEY WORDS: Proprioception - Arthrometry, articular - Swimming.

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The lumbar spine is a critical area of the mus- culoskeletal system engaged both during sports and in everyday life.[1] Its integrity and conscious control are necessary for its overall stability to support the weight of the body and voluntarily manage the center of mass of the body.[2] The

The lumbar spine, included in the popu- lar core area,[3] is furthermore essential because most of the body's mass is located in the lumbar area, and any change in lumbar movement can interfere with body posture, balance or body dis- placements.[3, 4]

Lumbar conscious control strongly depends on lumbar proprioception.[5] Proprioceptive acu- ity is significantly associated with the perfor- mance level achieved by elite athletes.[6, 7] Lumbar spine proprioception has been rarely studied in healthy active subjects or athletes, although it is accepted that having lumbar conscious pro- prioception provides better limb efficiency, core control, stability, and balance.[8, 9] Moreover, it is believed that the role of sensory-motor control is much more important than the role of strength or endurance of the trunk muscles in the search for balance between lumbar stability and mobility.[7]

Learning movement skills means develop- ing new patterns of movements by processing proprioceptive information appropriately. It has been argued that a novice athlete spends time consciously mastering new movements using a closed-loop system of control. On the other hand, skilled athletes only occasionally use sen- sory checking for successful execution of rel- evant movements.[10]

Sagittal plane movements have been the most commonly studied due the high incidence of lumbar injury and low back pain.[11, 12] Determin- ing lumbar conscious control or proprioception involves measuring the accuracy of joint-angle recognizing, which can be developed actively or passively in an open or closed-chain environ- ment, expressed by the Absolute Error (AEr).[13] To obtain an AEr, participants are required to re- port whether they are able to detect the stimulus, movement or joint position with one stimulus or ongoing stimuli.[14, 15]

Lumbar range of movement (ROM) has been studied to determine changes that could cause core instability, low back pain or other lumbar disorders.[16-18] Lumbar ROM is essential to de- velop effective movements during both daily liv- ing and sports activities, and it has been consid- ered to be an important factor in low-back pain, especially when the "Neutral Zone" (the region of intervertebral motion around the neutral pos- ture where little resistance is offered by the pas- sive spinal column) is increased.[19, 20] It is known that the normal lumbar ROM allows the body to respond better to external forces and prevent the majority of lumbar injuries.[4]

Methods reported to measure lumbar con- scious control and ROM have used the same devices: electromagnetic devices,[17] inclinom- eters,[21] and electrogoniometers.[22] The sensors of these devices are located on spinal process surfaces ranging from T_2 to S_1 or S_2 during flexion, extension and lateral bending in a standing or seated position with and without fixing the lower extremities.[16-18, 23-25] The most reliable and valid instruments to assess spine ROM are X-rays and MRI, but these instruments are associated with radiation and can be expensive.[18, 23] Perriman et al.[22] measured subjects in static positions using an electrogoniometer because the "clinical gold standard" is a static measurement.[22] Neverthe- less, to the best of our knowledge, there is no golden standard to assess lumbar proprioception or conscious control.[13, 26]

There is some evidence for better reliability for the active movements test than the passive movements test; poor reliability is often caused by inexperienced researchers and difficulties placing the device sensors in the right places.[27, 28] The lumbar spine and its muscles receive a lot of attention in most swimming strength training programs because it has been proposed that the core muscles contract during swimming to de- crease form resistance or drag on a swimmer's body to increase speed.[29]

In swimming, the maintenance of posture, balance and alignment is believed to be critical to maximizing propulsion and reducing drag.[29] Recently, it has been reported that differences among high-level swimmers in terms of perfor- mance stem from their ability to perform high- speed undulatory underwater swimming. Undu- latory underwater swimming efficiency depend on the lumbar range on movement, lumbar stiff- ness and the swimmers' ability to control and de- velop the maximal lumbar flexion and extension velocity, followed by the inertial movement of the hips, knees and ankles.[30]

In a sporting environment, core stability is defined as the ability to control the position and motion of the trunk over the pelvis to allow op- timum production, transfer and control of force and motion to the terminal segment in integrated athletic activities. Therefore, core stability is re- lated to both lumbar proprioception and ROM.[29] The sensory receptors subserving propriocep- tion include the ruffini, pacini, golgi tendons, and muscle spindles afferent receptor systems.[26, 31] These systems provide somatosensory input via the dorsal column-medial lemniscal pathways of the spinal cord to the mesencephalic reticu- lar formation, cerebellum, thalamic relay nuclei, and sensory cortex, and thence to parietal lobe areas 5 and 7 and to the premotor area.[32] In short, these systems are believed to subserve conscious proprioception. Position sense is largely medi- ated by activity in muscle spindles that respond to mechanical stimulus of traction.[31] Muscle spindles and the golgi tendon organs contribute to a sense of joint position only when the joint is moved to the limit of its range of motion. Histo- logical studies have described the spatial details of lumbar spine proprioceptors. These studies have revealed that deeper proprioceptors can be stimulated only at the end of the spine ROM.[33, 34] Therefore, there is a tight relation between affer- ent information and joint ROM due propriocep- tors being highly activated when a joint is moved to its maximal ROM and the mechanical traction that it receives is higher.[34, 35] Moreover, soft-tis- sue proprioceptors have more difficult detecting joint position or movement when the joint ROM is larger than when it is shorter due to the wide range of the soft tissue's tractions that the pro- prioceptors have to detect.[15, 31, 33] Moreover, the thresholds to activate these afferent neurons in soft tissue are higher because more time is neces- sary for maximal soft tissue elongation in higher- ROM joints than in smaller-ROM joints.[33, 35]

Although lumbar proprioception is likely to affect the swimming times of high-level swim- mers, most of the proprioception tests in swim- mers have been focused on the shoulders rather than lumbar control.[10, 36] Considering the im- portance of lumbar ROM and conscious control in lumbar health and sports attainment, there is no test that attempts to assess both outcomes simultaneously in able-bodied subjects. There- fore, the aim of this study was to design a new lumbar ROM and joint position sense (JPS) test using an electrogoniometer and to compare the differences between AEr and its percentage rela- tion with the total lumbar ROM (Relative Error (REr) values) between elite swimmers and active students. We hypothesized that larger joint ROM increases the proprioception challenge because it makes it difficult to stimulate proprioceptors that respond better at the limit of the joint ROM, and with higher ROM the higher are the amount of intermediate degrees to be indetified.[13, 33] We also hypothesized that swimmers would exhibit better lumbar proprioception scores than active students and a smaller lumbar ROM due their stiffer core muscles.

Materials and methods

Design

Cross-sectional repeated-measures study

Participants

A total of 61 subjects volunteered to participate in the study. The participants included 34 healthy elite swimmers from the senior Spanish nation- al team (mean age: 20.3±4.1 years, mean body mass: 71.7±10.6 kg, mean height: 1.7±0.1 m and mean body mass index (BMI): 22.2±2.2 kg/m^2 and 27 healthy physically active students (mean age: 22.8±2.9 years, mean mass: 70.8±8.5 kg, mean height: 1.7±0.1 m and mean BMI: 23.6±1.8 kg/m^2). The elite swimmers all had spent a mini- mum of 4 years on the Spanish swimming na- tional team, actively training 10.8±1.0 sessions per week and swimming for 39.7±2.1 hours per week and competing at the international level for at least 6 years. Active students reported practic- ing 4.1±1.6 sessions per week, which included 2.6±0.8 different activities such as soccer match- es, aerobic workouts or recreational running. In total, the students engaged in, on average, a total of 5.0±3.2 hours of physical activity per week.

We excluded subjects who had acute lower back pain or individuals who had suffered any lumbar injuries within last year that might influ- ence the neuromuscular control characteristics of the lumbar spine. We also excluded any sub- jects who had had pain in some other part of their body that prevented them from completing the necessary motions of the tests.

After being fully informed verbally and in writing of the purposes and potential risks of the study, the subjects provided their written consent to participate in the investigation. The study and its protocol were reviewed and approved by the Ramon Llull University internal review board and conducted in accordance with the latest ver- sion of the Declaration of Helsinki.

Equipment

We used an electrogoniometer (Transducer TS- D130A, Biopac Systems, Inc., United States) integrated with a computer and Acknowledge 3.0.9 software (Biopac Systems) to assess lum- bar electrogoniometer flexion, extension, total ROM and JPS degrees. We engaged in calibra- tion prior to each testing day to determine the 0° and 90° of each frontal and sagittal plane, but we only analyzed the sagittal data. The computer was calibrated with a sample rate of 500 Hz.

A manual chronometer (Namaste© model 898, Spain) was used to identify the interval in sec- onds over which the subjects maintained each position at the recorded degrees.

A computer was used to play a video explana- tion of the test while the goniometer was placed at the lumbar skin area. This technique ensured that the amount of information provided by the tester did not vary.

Different Swiss balls (Gymnic Plus Stability physioballs, TMI, Inc., Italy) ranging in diam- eter from 55–90 cm were used to ensure a cor- rect seated body position. The ball inflation was checked at 3 bars between tests to ensure that the diameter remained stable. We used three sizes of Swiss balls during the evaluation: 55 cm for subjects between 1.60 and 1.70 m tall, 65 cm for between 1.71 and 1.80 m tall and 90 cm for sub- jects between 1.81 m and 1.90 m tall.

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Procedures

The lumbar ROM and Proprioception Test (R&P- t) was designed to challenge the subject's ability to detect a neutral lumbar position on the sagittal plane between the maximal lumbar flexion and extension while sitting on a Swiss ball.

The subjects were interviewed to collect de- scriptive data and information regarding lumbar symptoms status and history and the types and frequency of each individual's physical activ- ity. All of the subjects returned to the laboratory 48–72 hours after testing for retesting using the same protocol. The participants were asked to continue with their normal daily activities or training sessions and not to practice the testing movements.

All of the tests were completed between 2 and 5 PM by the same primary investigator to mini- mize fluctuations in circadian lumbar ROM.[37]

The electrogoniometer was set to calibrate the 0° and the 90° each testing day. Therefore, flex- ion movements were associated with positive de- grees and extension movements were associated with negative degrees. However, all of the data were processed as absolute scores.

All of the testing procedures were recorded in a video file to ensure that all of the participants received the same amount of detail and informa- tion about the movements that they had to per- form during the test. While the subjects were watching the video explanations, the primary investigator fixed the electrogoniometer arms on each subject's skin using hypoallergenic tape; the cranial arm was placed over the T_{12} spinous process lined up with the L_3 level, and the lower arm was placed over the S_1–S_3 surface to assess the L_1– L_5 levels (Figure 1).

Once the goniometer arms were fixed, the sub- jects were asked to sit on the Swiss ball keeping their hips and knees between 80° and 90° of flex- ion with their back straight, their line of sight to the front and both hands over their knees in a re- laxed position. Once a participant was seated on the ball, the tester covered the subject's eyes with a black mask. The participant was then asked to move in both flexion and extension to ensure

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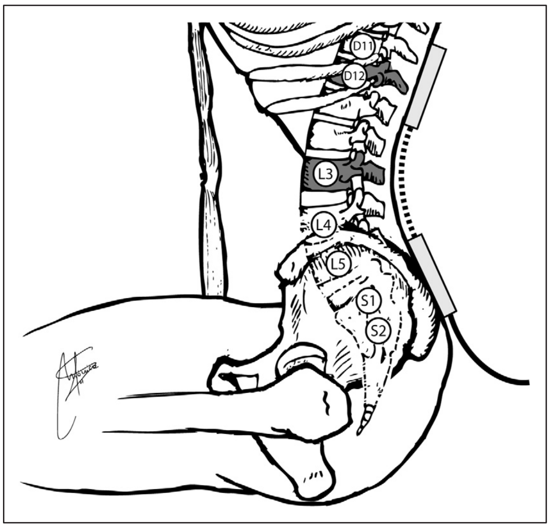

Figure 1.—Location where the primary investigator fixed the electrogoniometer arms.

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that there were no undesirable movements of the goniometer arms and that the testing position al- lowed for easy and balanced lumbar movements on the sagittal plane.

The subjects were asked to wear comfortable clothes to decrease pressure and tactile sensibil- ity and focus on the proprioceptive stimulus as much as possible.

When the subjects believed that they were comfortably seated and prepared, the researcher started to collect data by turning on the chronom- eter and the computer at the same time.

The subjects performed maximal lumbar flex- ion ($Flex_{max}$), maximal lumbar extension ($Ext-_{max}$) and the lumbar position that they felt was halfway between their maximal flexion and ex- tension ($P_{perceived}$) in three consecutive trials sep- arated by 20 seconds (Figure 2).

The researchers asked each subject to hold each position for 3 seconds. Furthermore, the subjects were advised when the time was up and they could move to the next position. The re- searcher did not provide any feedback and stood with a sagittal view during the entire test.

Lumbar ROM scores were obtained by sum- ming the mean flexion degrees and the mean ab- solute extension degrees collected in each trial.

AEr degrees were obtained based on the dif- ference in degrees of the real mathematical mid position (P_{real}) and the perceived mid position ($P_{perceived}$) (Figure 3).

REr percentages were obtained by dividing

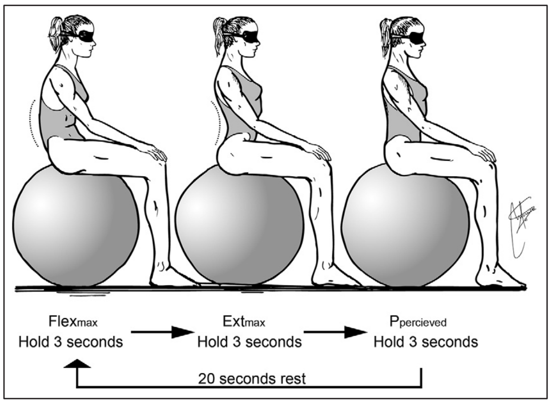

Figure 2.—Testing procedure and requested positions ($Flex-_{max}$: maximal lumbar flexion; Ext_{max}: maximal lumbar exten- sion; $P_{perceived}$: Mid perceived position between $Flex_{max}$ and Ext_{max}).

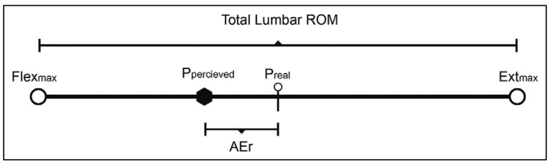

Figure 3.—Scores acquisitions (ROM: Range of movement; $Flex_{max}$: Absolute value for maximal lumbar flexion; Ext_{max}: Absolute value for maximal lumbar extension; $P_{perceived}$: Mid perceived position between $Flex_{max}$ and Ext_{max}; P_{real}: Math- ematical mid position of the total lumbar ROM degrees)

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AEr by the total ROM and multiplying the result by 100 (AEr/ROM ×100).

Test-retest reliability was determined by the reproducibility or stability on both test-retest data by comparing the scores between the means of 3 trials of each variable on the same subject on two different days separated by 2–3 days. Internal consistency reliability was determined by comparing the results of the 3 trials for each variable on the same subject and the same day.

Statistical analysis

Statistical analysis was performed using the SPSS statistical software package (version 22.0; SPSS Inc., United States). Significance was ac- cepted at $p<0.05$ for all of the tests. The Kolmogorov-Smirnov test was used to check the normal distribution of all of the variables.

Prior to processes the data using SPSS soft- ware, we measured the mean of the collected degrees over each 3-second interval of maximal flexion ($Flex_{max}$), maximal extension (Ext_{max}) and the perceived mid position ($P_{perceived}$) on the sagittal plane for each trial.

We used intraclass correlation coefficient to assess test-retest and internal consistency reliability using Hopkins' criteria of interpretation.[38] Factorial repeated-measures ANOVA was used to compare the lumbar flexion ($Flex_{max}$), exten- sion (Ext_{max}) and total ROM degrees, AEr and REr among the 3 trials in the same day and on both days between the elite swimmers and ac- tive students. In case of a significant F value, we used Bonferroni's multiple comparison tests to determine whether the means were different at $p<0.05$.

Group means and standard deviations (SDs) were calculated with a non-paired sample T-test to compare the differences among Ext_{max}, $Flex_{max}$, total ROM, AEr and REr between active students and elite swimmers. Cohen's *d* effect sizes were calculated using thresholds described by Hopkins et al.[38] as follows: 0.0−0.2 was triv- ial, 0.2−0.6 was small, 0.6−1.2 was moderate,
1.2−2.0 was large, and >2.0 was very large.

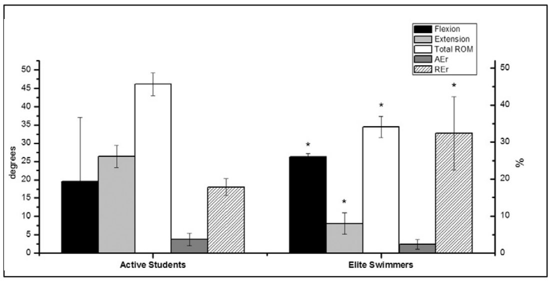

Figure 4.—Comparisons for mean scores of $Flex_{max}$, Ext_{max}, total ROM, AEr and REr between elite swimmers and active students. Values are presented as mean with SD.
*P<0.05 compared within groups.

Results

The results of the R&P-t internal consistency and test-retest reliability are listed in Table I. No dif- ferences were found between the trials in all vari- ables and the scores on the two different days.

The lumbar $Flex_{max}$, Ext_{max} and total lumbar ROM scores were significantly different between the swimmers and the students with moderate ef- fect size (ES). Active students exhibited moder- ately larger total lumbar ROM than swimmers (46.1±12.4 *vs.* 34.4±16.7, p=0.003, *d*=0.79).

The AEr scores exhibited trivial differences be- tween groups, and REr were significantly higher for swimmers that for students (28.9±35.7% *vs*. 15.7±11.3%, p=0.049, *d*=−0.5) (Table II, Figure 4).

Discussion

The results revealed that R&P-t is a high reliable method to assess both AEr and total ROM and to define the REr as the percentage of error con- sidering the AEr and the total lumbar ROM. The results showed that, despite elite swimmers and active students having non-significant differenc- es in AEr scores, the students had significantly higher REr and a consequently a poorer ability to consciously control their lumbar ROM.

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TABLE I.—*Intraclass correlation coefficients scores for both elite swimmers and healthy physically active students.*

Days of Testing	$Flex_{max}$ Trials	Ext_{max} Trials	ROM Trials	AEr Trials
Internal consistency				
Recreational (day 1)	0.97-0.98	0.96-0.98	0.93-0.97	0.94-0.97
Elite (day 1)	0.94-0.96	0.94-0.97	0.94-0.97	0.80-0.83
Recreational (day 2)	0.97-0.98	0.93-0.97	0.86-0.96	0.80-0.92
Elite (day 2)	0.81-0.95	0.94-0.98	0.94-0.97	0.80-0.87
Test-retest				
Recreational	0.91	0.92	0.85	0.80
Elite	0.93	0.98	0.98	0.81

Criteria used to interpret the magnitude of the ICCs were: >0.99 extremely high, 0.90-0.99 very high, 0.75-0.90 high, 0.50–0.75 moderate and <0.50 low reliability.

TABLE II.—*Absolute means of lumbar maximal flexion, extension and total ROM, AEr and REr between elite swimmers and healthy physically active students.*

	Recreational athletes	Elite swimmers	*d*	ES	P value	Recreational vs. Elite [95% CI] – Rating
Flexion (degrees)	19.6 (1.7)	26.3 (0.8)**	−0.92	moderate	0.002	[−10.5 to −2.7]
Extension (degrees)	−26.4 (3.0)	−8.1 (2.9)**	1.11	moderate	0.000	[−26.8 to −9.8]
Total ROM (degrees)	46.1 (2.3)	34.4 (2.8)**	0.79	moderate	0.003	[3.9 to 19.4]
AEr (degrees)	3.1 (1.6)	2.5 (1.3)	0.14	trivial	0.791	[−4.8 to 3.7]
REr (%)	15.7 (2.1)	28.9 (6.1)*	− 0.5	small	0.049	[− 26.3 to 0.06]

Values are presented as mean (SE).

*P<0.05 compared within groups. CI: confidence interval. ES: effect size *d*= Cohen's effect size. Criteria used to interpret the qualitative magnitude of the ES were: < 0.2 trivial, > 0.2–0.6 small, > 0.6–1.2 moderate, > 1.2 large.

Differences between elite swimmers and active students

We hypothesized that elite athletes had to ex- hibit better relative joint position sense because the lumbar position can interfere on their per- formance. This situation does not persist among the students, who were free of performance re- quirements. Nevertheless, our results revealed lower REr in swimmers because although they have lower AEr scores they have also significant lower lumbar ROM according with their stronger core muscles.

We found that although a conventional pro- prioception test demonstrated non-significant differences in AEr between active students and swimmers, the REr data revealed that swimmers had significant lower values than healthy active subjects. Previous studies have noted that higher AEr values are associated with lower JPS and poorer performance among swimmers.[36]

Additionally, lumbar JPS is likely to be very important in controlling hip movements dur- ing undulatory underwater swimming, which is considered to be one of the most important technical movements in high-level swimming races.[30] Generally, athletes need higher JPS than other active populations to improve their techni- cal ability and performance, and the present test yielded evidence that elite swimmers need better proprioception training to improve their lumbar conscious control, particularly to improve their underwater undulatory swimming performance and their lumbar position during training or com- petition.

Clinicians must consider this new test when assessing lumbar proprioception and ROM to quantify two important variables of core stabil- ity and to prevent lumbar risk factors in healthy individuals or athlete populations.[4]

Our results have shown that students have more Ext_{max} and total ROM, which is consistent with the results of previous studies of able-bod- ied subjects.[17, 24, 39] Active students also exhib- ited higher but not significantly different AEr scores than the swimmers. In general terms, in the absence of REr data, we can conclude that active students may have less JPS than elite swimmers. Because of their larger ROM, they are more likely to suffer from low-back pain.[40, 41] However, the REr scores revealed that students have smaller percentages of error considering that they have a larger total lumbar ROM than elite swimmers (Table II, Figure 4).

Testing procedures

The R&P-t is a new testing method for the assess- ment of functional proprioception of the lumbar spine in which subjects compare two movements and try to find an intermediate position between them. In the R&P-t, both movements have clear- ly defined start (lumbar $Flex_{max}$) and end posi- tions (lumbar Ext_{max}) of the total lumbar ROM. Therefore, subjects had multiple stimuli between the total ROM to detect the perceived mid posi- tion ($P_{perceived}$). The primary difference between our purpose and other proprioception measure methods is that we employed lumbar sagittal repositioning in an unknown position ($P_{perceived}$) to increase demands on proprioception sensing without providing any feedback to the subjects. We have tried to render the test more similar to the functionality of technical movement learn- ing: during both daily activities and swimming practice there is no feedback reporting the cor- rect lumbar position during the action. There- fore, subjects gave their feedback based only on input from proprioception afferent neurons. We used an electrogoniometer because it ensures both dynamic and static lumbar ROM that is free and functional. Furthermore, this device is inex- pensive and easy to use outside a conventional laboratory.[22] Sitting on a Swiss ball enables pel- vic movements and sacral movement freedom in a relaxed and balanced posture. It has been ob- served that fatigue did not set in as rapidly as in other studies that employed a standing test posi- tion.[42] Our methodology may explain the AEr of our sample having a larger SD than other studies (Table II).

The R&P-t exhibited higher reliability for lum- bar flexion, extension and total ROM values than previous similar studies, which reported ICCs that not exceed 0.15 for extension and 0.88 for lumbar flexion positions.[16, 17] Interobserver relability was not addressed in this study because we were primarily interested in the accuracy of the R&P-t for measuring REr differences be- tween elite swimmers and active students, which requires expertise of an observer rather than mul- tiple assessors. Test-retest reliability was, there- fore, more appropriate.

The present study has avoided some of the problems that have been reported in previous reliability studies to ensure better outcome sta- bility. We have avoided these problems by en- suring a stable room temperature, the same test explanations, masked eyes, comfortable clothing to avoid extra-tactile cues, and the same experi- enced tester.[28]

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We did not do the test validation. Neverthe- less, electrogoniometer validation has been re- ported for measurements of spine ROM[22] and there is no golden standard for proprioception tests. When comparing the scores of the pres- ent study with previous studies that assessed active lumbar ROM in a seated position and the same lumbar segment as the present study (L_1-S_1), we found similar mean values.[18] Other studies have reported a lumbar flexion signifi- cantly higher than that of this study (48±13° *vs.* 23.2±7.8°). This difference may be due to the assessment of total flexion without any restric- tion of hip movement.[43] In the present study, we restricted lumbar flexion by preventing any anterior bending of the hips or trunk; the sen- sors of the electrogoniometer just measured the lumbar segment from L_1 to L_5. When we com- pared our flexion values with Biplanar X-ray data, we found values of 52.0 4.2°,[23, 44] which is far from the accepted 14° difference.[45, 46] It is important to note that assessing lumbar flex- ion with X-ray, data directly measures vertebral movement.[23] Conducting measurements with any other surface equipment results in ROM restrictions from the soft tissues around the spine. Moreover, we find that the present Flex- $_{max}$ values were similar to those of other studies that used goniometry with an 3Space Isotrack, an Epionics Spine System or inertial measure- ment.[16, 17, 24]

When we analyzed the Ext_{max} mean results (15.8±18.9°), we find found that they were much more similar to X-ray data (16.0±2.2°) and to three-dimensional motion analysis systems (18.4±6.0° in females and 19.4±8.3° in males) than other reported studies.[23, 47] In the pres- ent study, elite swimmers had reduced Ext_{max} degrees with respect to the students or to other less-active subjects in comparable studies (Ta- ble II).[17, 23, 24] This fact is likely due to the tests starting in a seated position, which rendered the lumbar spine begin from flexion position. Fur- thermore, the extension movements were more challenging and decreased by the participants' fatigue. It is possible that the anterior core stiff- ness of elite swimmers plays an important role in reducing lumbar extension because core sta- bility training is much more involved in profes- sional swimmers than other active populations. When we compared our AEr findings (Table II, Figure 4) with the findings of other similar stud- ies, we recovered values similar to other lumbar spine proprioception studies that used a Biodex System Isokinetic dynamometer and electromag- netic 3Space tracking systems, which are consid- ered to be the most accurate for assessing JPS.[46] The primary difference between our findings and those of other studies lies is in the SD, which was much larger in our study. This situation likely stems from the fact that this study was the only one that asked subjects to reposition their spine in an unknown mid position between maximal lumbar flexion and maximal extension ($P_{perceived}$) (Figure 3); other studies asked participants to re- peat a known position.[48, 49]

Conclusions

The R&P-t is the first reliable test to assess both proprioception and ROM with the same equip- ment in the lumbar spine. Moreover, we added extra information: the REr. A higher AEr in a re- duced ROM implies higher relative joint insta- bility, and the same AEr in a larger ROM means more relative control over this joint. Assessing three outcomes with the same test could provide practitioners with important information about lumbar status without having to spend extra time on different tests. We expect that this progress will make it possible to approach training test- ing from a holistic and individualized perspective.

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