SPEED-DEPENDENT INCREASE IN LUMBAR LORDOSIS IS INCONSISTENT WITH SPEED-INDEPENDENT PELVIC TILT DURING TREADMILL RUNNING

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Lumbar lordosis (LL) is considered as an important factor of low back pain. Although LL during running (dynamic LL) and anterior pelvic tilt (APT) are thought to increase simultaneously, this relationship has not been examined when running speed is changed. Here we show that dynamic LL increases with the increase in running speed, whereas APT is invariant during treadmill running at 4.0, 5.5, 7.0 and 8.5 m/s in 18 male collegiate athletes. The speed-dependent increase in dynamic LL suggests that runners and coaches should be cautious that greater mechanical load on the lumbar spine might occur during faster running. The inconsistent sensitivity of the lumbar spine and the pelvis to the increase in running speed suggests that practitioners and clinicians should assess LL separately from APT, especially during faster running.

KEYWORDS: trunk control, lumbo-pelvic movement, sprint, curvature, hyperextension.

INTRODUCTION: Low back pain is a common problem in athletes which accounts for 12–15% of time-loss injury which causes at least 3 weeks absence from normal athletics activity (Jacobsson et al., 2012). High prevalence of specific spinal pathologies caused by repetitive loading have been reported in athletes (Lawrence et al., 2006). A better understanding of the cause of lumbar mechanical load facilitates participation to competitive activities.
Lumbar lordosis (LL) is an important factor of low back pain. Greater LL or hyperextension of lumbar spine is associated with spondylolysis (Leone et al., 2011), and increases the mechanical load on the posterior element of the lumbar spine (Inoue et al., 2020). Excessive LL during running [defined as dynamic LL (Castillo & Lieberman, 2018)] can lead to large mechanical load on the lumbar spine. Trunk extensor muscles have their insertion on posterior elements of each vertebra and their action is in a direction to increase LL (Been & Kalichman, 2014). The increase in trunk extensor muscle activity (Cappellini et al., 2006) and the lumbosacral extension torque (Sado et al., 2019) with the increase in running speed has been observed; therefore, dynamic LL might increase with the increase in running speed.
Sagittal position of the pelvis is associated with LL in static standing (Boulay et al., 2006; Levine & Whittle, 1996). Greater anterior pelvic tilt (APT) has also been considered as an indicator for excessive LL during running (Schache et al., 1999). However, it is unclear whether APT changes similarly to LL in response to the increase in running speed. Although the increase in the lumbosacral extension torque with the increase in running speed appears to increase APT (Sado et al., 2019), the increase in hip extension torque (Sado et al., 2016; Schache et al., 2011) might cancel out its effect on APT. Given that dynamic LL is speculated to increase with running speed, the speed-dependency in dynamic LL might differ with that in APT.
We examined the speed-dependency in dynamic LL and APT. Our main hypothesis was that dynamic LL increases with the increase in running speed, but APT is invariant. If this hypothesis is proven, the results will provide evidence that APT is not a proper indicator for LL and potential injury risk.

METHODS: The *a priori* power analysis (Wilcoxon signed rank-sum test for paired samples, α = 0.050/6 = 0.0083, 1-β = 0.80, Cohen's d = 1.20) indicated that the minimum number of participants required was 13. Based on the results of *a priori* power analysis, 18 male collegiate

athletes include nine sprinters, three jumpers and six decathletes [21.8 ± 1.7 years; 1.75 ± 0.05 m; 67.8 ± 5.0 kg; 100 m personal best time, 11.05 ± 0.32 s; World Athletics score, 914 ± 104] were recruited. All participants provided written informed consent. This experimental procedure was approved by the Human Research Ethics Committee at University of Tsukuba (PE023-5). Participants performed treadmill running at four different speeds. All participants wore close-fitting clothing and their own running shoes. The marker set was similar to (Sado et al., 2020). In addition, 18 tracking markers, 6 mm in diameter, attached on spinous processes of C7–L5 vertebrae to capture detailed spinal behaviour. After a self-directed warm-up and a familiarisation period with the treadmill running at the same speed as the trials, participants performed static standing. Then the participants ran once each at 4.0, 5.5, 7.0 and 8.5 m/s on a treadmill (ORK-7000, Ohtake Root Kogyo, Iwate, Japan). At the beginning of each trial, participants jumped onto the belt while holding the handrails after the belt had reached the speed for each condition. After 3–5 strides from releasing the handrails, the running motion was recorded for five stride cycles. The number of strides was determined to ensure that participants could complete all the trials stably. Whole trial requires 15–20 strides for each condition. For injury prevention, the order of running speeds was incremental, and participants were strapped into specially designed harness so as to make spinal markers visible from the cameras. Participants rested at least 3 minutes between trials to avoid the effect of fatigue. An 11-camera motion capture system (Mac 3D, Motion Analysis Corporation, CA, USA) recorded the 3D coordinates of the position of the reflective markers (sampling rate, 200 Hz).
Data analyses were performed using MATLAB 2023a (MathWorks Inc., Natick, MA, USA). Position coordinates of the markers were smoothed using a fourth-order Butterworth low-pass digital filter with a cut-off frequency of 9.4–13.0 Hz based on residual analysis.
LL was assessed by a central angle of the best-fit, least-square circle for the markers on the T12–L5 spinous processes for each frame (Castillo & Lieberman, 2018) (Fig. 1). APT angle was defined as the first rotation of the Cardan (xyz sequence) angle of the pelvis relative to the global coordinate system. As dynamic LL and APT display two peaks for each stride cycle (Castillo & Lieberman, 2018; Schache et al., 1999), maximal dynamic LL (dynamic LL_{max}) and maximal APT (APT_{max}) was computed as an average of two peaks for each stride cycle (Fig. 2A and 2C).
Descriptions for angle data were mean ± SD calculated using circular statistics (Berens, 2009). The intraclass correlation coefficient (ICC) was used to assess the reliability of the dynamic LL_{max} and APT_{max}. The averages of each variable over five stride cycles were used as representative value of each participant. The Wilcoxon signed rank-sum test for paired samples was used to test the difference in dynamic LL_{max} and APT_{max} between four running speed conditions. Overall alpha level was *a priori* set to 0.05. To control the family-wise error rate in each multiple comparison, the alpha level was modified by the Bonferroni adjustment for all tests.

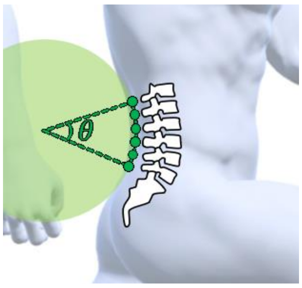

Figure 1: Schematic drawing of lumbar lordosis defined as central angle of best-fit circle.

RESULTS: “Excellent” reliability was confirmed for dynamic LL_{max} (ICC ≥ 0.99) and APT_{max} (ICC ≥ 0.93) at all running speeds. The pattern of dynamic LL and APT were similar across all running speeds, showing biphasic oscillation in each stride cycle (Fig. 2A and 2C). Dynamic LL_{max} increased significantly for all running speed increments ($p \leq 0.002$; from 28.3 ± 8.1 deg for 4.0 m/s to 35.4 ± 9.3 deg for 8.5 m/s) (Fig. 2B). No significant differences in APT_{max} were found between all running speeds (p = 0.231–0.648) (Fig. 2D).

DISCUSSION: We found that dynamic LL_{max} increased with the increase in running speed. The speed-dependency of dynamic LL_{max} supported our hypothesis. Considering the non-linear load-displacement relationship of the lumbar spine (Panjabi et al., 1994), the greater the LL, when forces and torques are applied to the spine, the greater the risk of increasing the mechanical load on the lumbar vertebrae and peripheral tissues. From a force (Weyand et al., 2010) and torque (Sado et al., 2019) perspective, it has been suggested that the higher the running speed, the greater the mechanical load on the lumbar spine. We further add that the

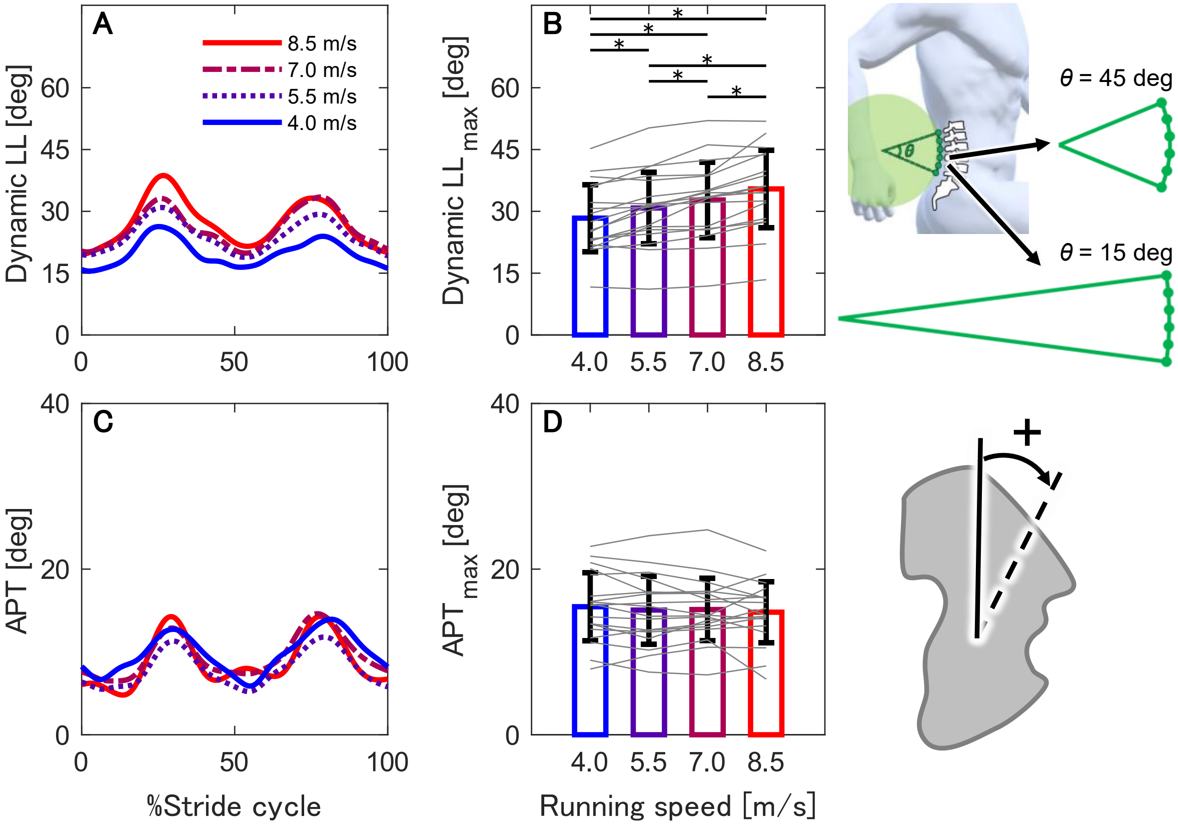

Figure 2: Time series data for dynamic lumbar lordosis (LL) (A) and anterior pelvic tilt (APT) (C) from a representative participant, maximal Dynamic LL (LL$_{max}$) (B) and APT (APT$_{max}$) (D) . Grey lines in B and D represent the values from each participant. Schematic drawing on the right of B and D shows the examples for shape of lumbar spine when central angles are 45 deg and 15 deg and definition of anterior pelvic tilt, respectively. * denotes significant difference ($p < 0.0083$).

higher the running speed, the greater the LL, thereby reinforcing the notion that the lumbar spine is exposed to greater mechanical load during faster running from an additional postural perspective. We suggest runners and coaches to pay close attention to avoid excessive LL especially when training at faster running speed.

Dynamic LL$_{max}$ was speed-dependent, while APT$_{max}$ showed no notable differences between all running speeds. This inconsistency supported our hypothesis. APT has been considered as indicator of LL and injury risk (Schache et al., 1999). However, our results suggest that APT was inconsistent with the increase in LL associated with the increase in running speed. Therefore, despite greater mechanical load in faster running, LL and potential injury risk would be underestimated when APT is used as alternative index. From a practical perspective, we suggest practitioners and clinicians to assess LL separately from APT, especially during faster running. Since dynamic LL cannot be measured in the field, developing alternative indices or devices to easily assess dynamic LL would be valuable for athletes and coaches.

Measurement of lumbar curvature revealed a discrepancy between the LL and APT sensitivity to running speed. This can be explained by the lumbo-pelvic-hip kinetics and the spinal deformity. The trunk extensors increase LL and APT, but the action for APT can be cancelled out by the hip extensors acting on the pelvis (Sado et al., 2016). The conventional approach, which models lumbar region as a single rigid segment, overlooks the unique lumbar behaviour with faster running. We highlight the importance of assessing flexible behaviour of the lumbar spine for a better understanding of the lumbo-pelvic movement and injury prevention.

There are several limitations in this study. First, this was observational study and did not examine the influence of dynamic LL on injury occurrence. We cannot directly discuss whether the increase in LL observed in this study is meaningful in terms of injury risk, which is an important future theme. Secondly, we used skin markers to assess the LL and did not measure the posture in each vertebral level. For example, if the inter-marker distance increased, our method could not distinguish whether this increase was caused by translational or rotational vertebral movements. It will be informative to measure each vertebral posture during running, e.g. using three-dimensional radiography, to estimate the mechanical load on the lumbar spine. Thirdly, all participants are adult male sprint-related athletes. It is known that sprinters have greater LL than average, and that age and sex may also influence LL (Been & Kalichman, 2014). Thus, the results of this study should be applied cautiously to other populations, such as ball sports players, children, and female athletes.

CONCLUSION: We showed speed-dependent increase in dynamic LL, which highlighted severity of the mechanical load on the lumbar spine from the postural perspective. We further found the inconsistency in the speed-dependent postural change between lumbar spine and pelvis. Contrary to the general understanding that the lumbar and pelvic movements are closely linked and coincident, we provided an example of inconsistent behaviour between the lumbar spine and the pelvis. Our practical implications are that greater mechanical load on the lumbar spine might occur in higher speed range, and that athletes and coaches should pay close attention to the posture of the lumbar spine separately from the pelvis.

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