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Original Article

Temporal changes of pelvic and knee kinematics during running

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Abstract:
Problem statement: Continuous running for a long duration during training and competition can lead to injuries due to changes in lower extremity kinematics particularly in pelvic tilt and rotation. These changes of pelvic kinematics may serve as a warning sign of instability structures and present an injury risk. **Objective:** To investigate the change of pelvic and knee kinematics during running at different time points (1st, 10th, 20th, and 30th minute). **Materials and methods:** During the first visit, VO2max test was performed on twelve recreational runners. During the second visit, 3D motion analysis was performed, and kinematics data were collected while the participants ran on a treadmill at a speed of individuals' 70% of VO2max for 30 min. Pelvic and knee kinematics in all three planes (including pelvic range of motion, pelvic angles, knee angles) at the 1st, 10th, 20th, and 30th min of 5 running gait cycles were obtained and analyzed. Additionally, step and stride lengths were analyzed. **Results:** One-way repeated measures ANOVA revealed no significant differences in the kinematics of knee and pelvic angle and no significant differences in step and stride lengths at initial contact (IC) and toe-off (TO) during running for 30 min. **Conclusion**: It is possible that the runners are used to their own pace and have the ability to maintain a running pattern. Therefore, this work may be beneficial for the coaches, runners, and sports scientists to understand the changes of the pelvic and knee mechanism during running overtime to improve training and reduce injury risk. Additionally, this work provides a practical overview to observe the lower extremities of running mechanics during different time points.
Key Words*:* **running gait, recreational runners, motion analysis, time series**..

Introduction

Running is one of the most popular activities for health, well-being, and professional sport. The number of people engaged in running has continuously increased over the past decades owing to the concept of engaging people in physical activity such as Park Run and couch to 5 km (Van Middelkoop et al., 2008). Running has a variety of types and distances, e.g., short, middle, and long-distance running. To succeed, collaboration between the whole-body musculoskeletal system and other systems is important to produce horizontal velocity (Yamato et al., 2015). Indeed, the majority of action during running involves the pelvis, lower extremities, and muscles that are attached to the pelvis and crossed lower limb joints to develop step length and step frequency and consequently moving the body forward. Furthermore, the goal of locomotion is to transport the body center of mass by minimizing upward movement and maximizing forward movement (van Oeveren et al., 2021). Many running biomechanics studies investigated gait cycles and mainly designed target interventions to enhance running performance and reduce injury risk (Derrick et al., 2002; Silvernail et al., 2015; DeVita et al., 2016). In terms of kinematics to increase running velocity, runners increase stride length by changing pelvic and knee movement during the stance phase to produce longer step distance (Novacheck, 1998). Generally, lower extremity joint moments at the hip, knee, and ankle joints have been shown to increase when runners desire to increase stride length to produce higher horizontal velocities (Ardestani et al., 2016). The movement pattern in lower extremities at different speeds can be appropriately adjusted by an individual runner, for example, by adjusting joint angles and stride length (Möhler et al., 2021). Similar patterns of lower extremity motion during running are reported but the range of motion (ROM) of joints during higher velocities is different; for example, with an increase in speed, flexion is increased in the knee joint, while extension is increased in the hip joint (Fukuchi et al., 2017). However, when lower extremity joints are limited by ROM, the increase in stride length is due to generating pelvic ROM during running, which may facilitate the forward movement in the lower extremities (Kerrigan et al., 2001). Previous studies have suggested that the pelvic tilt angle increases according to generating greater movement speed. During running, pelvic obliquity has been shown to be similar, and pelvic rotation has been observed to be different compared to walking (Novacheck, 1998).

As expected, lower extremities are a common site of injuries during running. These injury occurrences are mostly due to the chronic exposure to repetitive actions during long distance running that are experienced during training and competition. Errors in technique during training account for 90% of injury risk factors

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(Fredericson & Misra, 2007). The knee remains the joint with the highest incidences of injury (7.2–50%) during long-distance and street running (Van Middelkoop et al., 2008, De Oliveira et al., 2015, Benca et al., 2020), and it is the site of over 40% of all lower extremity injuries (Benca et al., 2020). The hip/pelvis incidences of injury is 8.5% (Benca et al., 2020). Currently there is a lack of clarity regarding the volume of running that may cause or predispose an athlete to an injury, especially in recreational runners. The number of injuries per hour of exposure is commonly used as a standardized measure of association. To our knowledge, only one systematic review and meta-analysis study reported that novice runners had 17.8 injuries per 1000 hours of running compared to 7.7 injuries per 1000 hours of running for recreational runners (Videbæk et al., 2015). It is possible that the changes in knee and pelvic kinematics due to continuous running for a long duration may be involved in potential injury.

Previous studies have reported that middle-distance and long-distance runners have more knee flexion and adduction at IC and peak knee extension during the stance phase (Tian et al., 2020; Möhler et al., 2021). Other studies have reported a relationship between kinematics changes and injury incidence, for instance, iliotibial band syndrome caused by increased knee adduction and peak knee internal-rotation angles (Aderem & Louw, 2015; Stickley et al., 2018) at stance phase and excessive abduction of the knee associated with ACL injury (Numata et al., 2018). Another study showed a relationship between pelvic motion, particularly the tilt and rotation, and running distance (Koopmann et al., 2019) and suggested that this motion was a warning sign of instability and led to higher stress on pelvic structures, which presented a serious injury risk. Therefore, the aim of this study was to investigate the changes in pelvic ROM, pelvic angle, knee angle, stride, and step lengths at different time points (1st, 10th, 20th, and 30th minute). We hypothesized that running for 30 min with speed at 70% of VO2max (individual speed) would produce differences in pelvic and knee kinematics. The overall objective of this study is to inform coaches about the key running mechanics and provide a safer environment for the runners to prevent or avoid an injury risk. The outcome is that running training will become more effective, efficient, and safe.

Materials and methods

Participants

Twelve healthy runners (9 males and 3 females) volunteered for this study. The age of participants was 37.92 ± 6.36 years, the weight was 66.17 ± 8.83 kg, and the height was 169.25 ± 8.74 cm. The average running speed on a treadmill was 7.49 ± 2.08 km/h, the average distance was 3.75 ± 1.04 km, and the average maximal oxygen consumption was 44.22 ± 8.39 ml/kg/min. All participants signed consent and ethical approval form before participating in the study (MU-CIRB 2019/132.0808). Recreational runners recruited for this study regularly ran at least 25 km per week and completed at least 1 minimarathon. All participants were excluded from this study if they had 1) pelvic and knee misalignment, 2) lower extremity injury, or 3) previous lower limb surgery in the past 6 months.

Testing procedure and data analysis

The data collection consisted of two visits. During the 1st visit, participants warmed up on the treadmill at a self-selected running speed for 5 min before starting the VO2max procedure. Then, the participants were asked to perform a maximal oxygen consumption (VO2max) test, which was later used to calculate treadmill speed at 70% of VO2max (running speed = 7.49 ± 2.08 m/s). All participants were asked to avoid high-intensity exercise and caffeine before the experiment testing day. For the 2nd visit, participants' 3-dimensional (3D) kinematics data were collected using 8 optoelectronic cameras (OptiTrack, NaturalPoint, USA) at 100 Hz. All participants wore their own running shoes, and the lower limb and trunk marker model was employed in this study (Vanrenterghem et al., 2010). Once the participants sufficiently warmed up, they ran on the treadmill (Walkerview, TecnoBody, Italy) at 70% VO2max for 30 min. The kinematics data of 5 running cycles were simultaneously collected at the 1st, 10th, 20th, and 30th minute at the sampling rate of 100 Hz. The Visual 3D software (C-motion, version 6) was used to analyze the 3D kinematics variables including pelvic ROM, pelvic angle, and knee angles. Five running gait cycles were time-normalized to 100%. All marker trajectories were filtered at 9 Hz by a Butterworth low pass filter from the location of the three-dimensional coordinates of the markers placed on the body.

Table 1 shows the definition of the main variables including pelvic ROM, pelvic and knee angle.

Variables	Definition
Pelvic angle ROM	The range of pelvic angle at IC to TO
Pelvic angle	Pelvic anterior (-)/posterior (+) tilt, pelvic abduction (-)/adduction (+) obliquity, pelvic internal (-)/external (+) rotation at IC and TO
Knee angles	Left and right knee flexion (-)/extension (+), abduction (-)/adduction (+), internal (-)/external (+) rotation angle at IC and TO

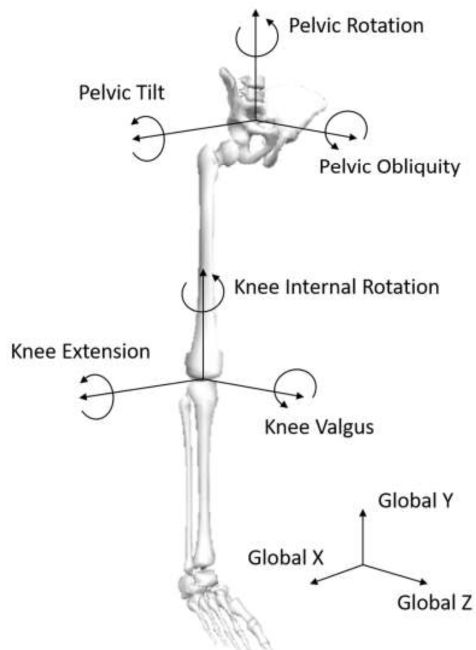

Figure 1 illustrates the kinematic model of the pelvis motion described with respect to the global coordinate system, and the knee motion was described with respect to the local coordinate system.

Statistical analysis

The SPSS for Windows (Version 18.0, Chicago, IL, USA) was used for all statistical analyses. Shapiro–Wilk test was used to determine the normal distribution of continuous data. One-way repeated-measures ANOVA was used to evaluate significant differences within each time point. The level of statistical significance was set at $P < 0.05$.

Results

An example of the comparison of both left and right knee joint angles and pelvic joint angle during the running gait cycle of one participant is shown in Figures 2 and 3, respectively. The figures show similar patterns between left and right knee angles as well as a similar pattern of pelvic angle in all three dimensions over time.

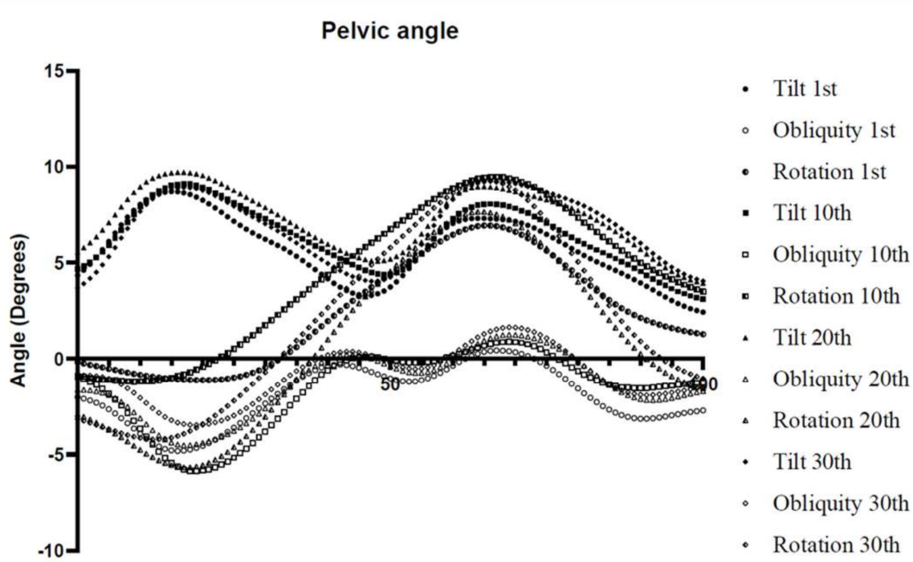

Figure 2 shows the left (top panel) and right (bottom panel) knee joint angles for running at 1st, 10th, 20th, and 30th minute for one participant.

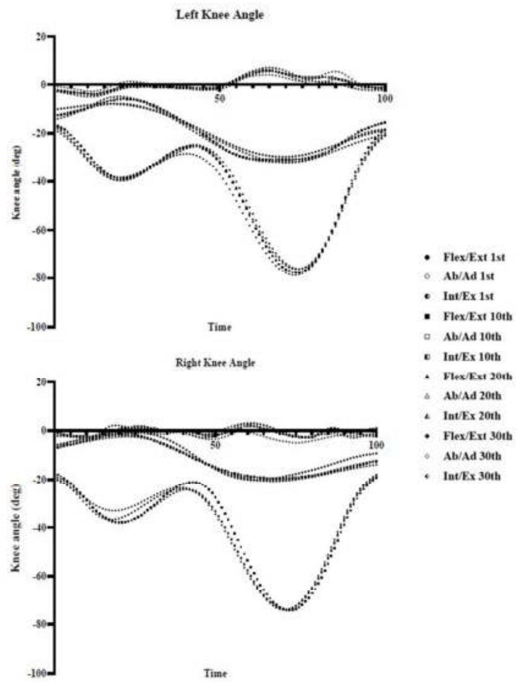

Figure 3 shows the pelvic angle for running at 1st, 10th, 20th, and 30th minute for one participant.

Figure 2 shows that both knee angles produced the greatest flexion movement in the sagittal plane during running and lesser movement in the transverse and frontal plane, respectively. However, the left knee angle revealed more abduction in the second half of running period, whilst, the right knee angle did not show a considerable change in the frontal plane. Nevertheless, both left and right knees showed internal rotation.

Figure 3 shows that during running at 1st, 10th, 20th, and 30th minute, the pelvic angle had slight movement in the sagittal and frontal planes and higher movement in the transverse plane. The pelvic tilt angle at IC showed moving of approximately 5°, which increased to almost 10° and decreased back to approximately 5° followed by an increase. In addition, it was observed that the pelvis underwent upward obliquity in the first half of the gait cycle, while external rotation was revealed in the second half of the running gait cycle.

Table 2 shows the mean and standard deviation of pelvic and peak knee angles during running at the 1st, 10th, 20th, and 30th minute. The obtained result showed that the pelvic angle at IC, TO and pelvic ROM was not significantly different in all 3 dimensions during the running time. Similarly, there was no significant differences between both sides of the body for knee angle during running at the 1st, 10th, 20th, and 30th minute.

Table 2 Mean ± SD of 3-dimensional pelvic and peak knee angles during running at 1st, 10th, 20th, and 30th minute

Variables	1st min	10th min	20th min	30th min	*P-value*
Pelvic angle @ IC					
Pelvic tilt (°)	1.01±2.13	0.86±2.26	0.60±2.86	0.70±2.65	0.233
Pelvic obliquity (°)	−0.43±1.57	−0.43±1.19	−0.68±1.46	−0.78±1.87	0.450
Pelvic rotation (°)	−2.47±2.78	−2.37±2.73	−2.67±2.15	−2.78±1.78	0.709
Pelvic angle @ TO					
Pelvic tilt (°)	−0.64±2.95	−1.08±3.54	−0.69±3.16	−1.00±3.69	0.659
Pelvic obliquity (°)	0.90±2.14	2.01±1.94	0.85±2.28	2.33±2.05	0.552
Pelvic rotation (°)	0.14±3.94	2.86±3.61	0.35±3.97	2.92±3.40	0.220
Pelvic ROM					
Pelvic tilt (°)	5.59±2.03	5.54±2.43	5.69±2.61	6.16±3.27	0.499
Pelvic obliquity (°)	5.13±0.88	5.36±1.59	5.40±1.47	5.42±1.04	0.788
Pelvic rotation (°)	6.72±3.13	7.38±2.73	7.76±2.75	7.41±3.40	0.088
Knee angle @ IC					
Left knee flex/ext (°)	−13.55±2.21	−14.45±2.76	−13.48±3.31	−13.41±3.12	0.457
Left knee ab/ad (°)	0.07±2.25	0.29±2.3	0.26±2.45	0.59±2.4	0.457
Left knee int/ex (°)	−10.17±4.15	−11.75±4.61	−10.61±4.48	−11.36±5.06	0.494
Right knee flex/ext (°)	−11.95±7.55	−12.43±6.88	−12.32±7.10	−12.62±6.90	0.831
Right knee ab/ad (°)	0.84±3.95	1.91±4.68	1.67±4.41	1.65±4.64	0.495

Right knee int/ex (°)	−13.91±4.47	−13.84±4.74	−13.69±4.74	−13.95±5.00	0.556
Knee angle @ TO					
Left knee flex/ext (°)	−18.22±4.89	−18.44±5.27	−18.15±4.62	−18.70±5.00	0.698
Left knee ab/ad (°)	−1.44±3.11	−1.26±3.34	−1.82±3.12	−1.57±3.22	0.137
Left knee int/ex (°)	−12.18±9.27	−13.49±9.74	−13.14±9.37	−13.21±9.27	0.484
Right knee flex/ext (°)	−19.86±6.22	−20.68±6.29	−20.78±6.15	−21.09±5.90	0.132
Right knee ab/ad (°)	−0.64±3.00	0.21±3.69	0.02±3.86	−0.50±3.27	0.637
Right knee int/ex (°)	−13.69±8.42	−15.63±8.57	−15.16±8.51	−14.74±8.95	0.084

The mean stride and step lengths during running at 1st, 10th, 20th and 30th min are shown in Table 3. Both left and right stride lengths were not significantly different over 30 min of running. In addition, there was no significant differences in step length when comparing each of the 4 running times.

Table 3 Mean ± SD of left and right step length during running at 1st, 10th, 20th and 30th minute

Variables	1^{st} min	10^{th} min	20^{th} min	30^{th} min	*P-value*
Left step length (m)	0.50±0.96	0.50±0.09	0.52±0.09	0.51±0.09	0.117
Right step length (m)	0.52±0.10	0.52±0.10	0.52±0.10	0.53±0.10	0.076
Stride length (m)	1.02±0.21	1.03±0.19	1.04±0.18	1.04±0.18	0.058

Pelvic anterior/posterior tilt angles at TO (a) shows similar patterns within individual's subjects time points; however, inter-individual variability was demonstrated (Figure 4). Nevertheless, both knee flexion angle of all participants (b & c) present similar pattern at 1st, 10th, 20th, and 30th minute of the trial (Figure 4).

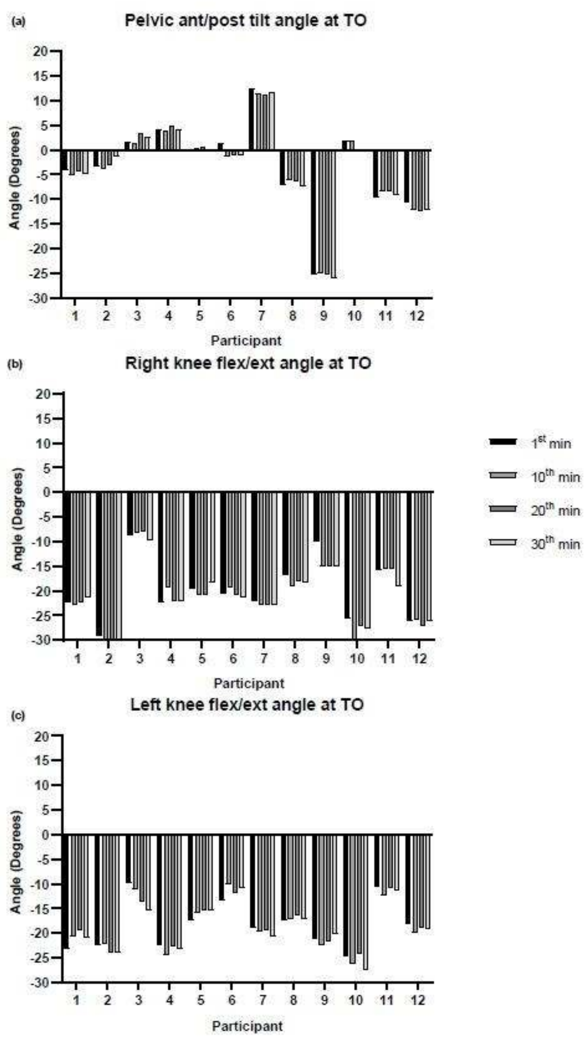

Figure 4 shows an example of pelvic and right and left knee angles including a) the pelvic anterior/posterior tilt angle and b) right knee flexion and c) left knee flexion angle of each individual between running at 1st, 10th, 20th, and 30th minute at TO.

Discussion

With running being a global activity undertaken by billions of people, reducing risk of injury is desirable. This study aimed to examine changes in pelvic ROM and angle, knee angles, step frequency, and step length during the 1st, 10th, 20th, and 30th minute of running, with the overall purpose of exploring the risk of injury associated with continuous running. This study hypothesized that continuous running over prolonged period of time would cause kinematic changes in the performer, specifically, in pelvic ROM and angle, knee angles, step and stride lengths at different time points. The main finding of this study, did not support the hypothesis because no significant differences in the 3D kinematics were observed for the knee and pelvic angles at IC and TO during running over these time periods. In addition, there was no significant difference between spatial gait variables related to step and stride lengths. The lack of change in the joint kinematics during the 30-min run is interesting because this highlights the performers' ability to maintain their techniques at their individual running speed. These results, although showing no differences, provide an important contribution in terms of an insight into the biomechanical changes that result as a function of running over time.

The findings of Willwacher et al., (2020) agree with those in our study; the abovementioned researchers observed no significant difference in peak knee angle in frontal and transverse planes. Willwacher et al. (2020) investigated altered lower extremity kinematics during running for 0–10 km in recreational and competitive runners whose best running times were faster than 37.30 min and the slowest running times were slower than 47.30 min in a 10-km run. However, of note, the study by Willwacher et al., (2020) examined runners who ran for longer than 30 min (Willwacher et al., 2020). In addition, van Oeveren et al. (van Oeveren et al., 2021) stated that most of the body's movements during running occur in the sagittal plane, e.g., the motion of knee kinematics at the sagittal plane during 30 min of treadmill running. It is possible that runners are comfortable with their own pace; therefore, the results obtained in this study represent the ability to maintain a running pattern. Running gait pattern is often adapted by runners under fatigue and may increase energy use, which increases the overuse injury risk (Derrick et al., 2002; Van Gheluwe & Madsen, 1997). Runners have their own gait "signature" based on their running economy; however, constant speed during strenuous running influences energy expenditure, which may alter gait patterns. However, in this study, the pelvic and knee kinematics did not show any changes. Previous studies have reported that knee flexes 12–37° during the stance phase (Fukuchi et al.,2017; Möhler et al., 2021), which is consistent with the findings of this study. Kellis et al. (2009) investigated lower limb kinematics changes by induced knee muscle fatigue during running. Similar to our findings, they observed an increase in knee flexion angle during TO compared to an unfatigued state (Kellis & Liassou, 2009).

Changes in pelvic angle have been reported to increase the risk of injury (Franz et al., 2009). For example, an increased anterior pelvic tilt during running has been cited as a factor for hamstring strains (Geraci Jr, 1996). In addition, iliotibial band syndrome is associated with increased pelvic obliquity during running (Schache et al., 2002). However, there are few studies that clearly explain the relation between pelvic axial rotation and injury risk while running. Previous studies reported that the kinematic pattern of pelvic rotation during running is different from that during walking (Schache et al., 2002). During walking, the pelvic motion exhibits maximal rotation in the left side at right IC, which supports our finding that during running at IC, the pelvic maximum rotation has been also shown. During the running phase, the pelvis motion is no longer required to be engaged with the lower extremities due to loss of the double support, as a stride lengthening mechanism. In general, runners who keep their pelvic segment in a stable position are better able to control their lower limb muscles during running. Williams et al. (1991) explained the mechanics of body changes during fatigue; they stated that regardless of fatigue impact on body kinematics, runners must keep their technique, which is less altered because excessive movement may enhance fatigue effect and degenerate the running technique (Williams et al., 1991). Moreover, previous studies have highlighted that runners under fatigued conditions had an increasing step length, which was not observed in this study where the step length and stride length remained constant over 30 min. It is possible that our participants were not sufficiently fatigued to incur a kinematic change. Interestingly, a previous study (Hanley & Mohan, 2014) has reported no changes in step length before 5 km during running on a treadmill. The average running speed in this study was 7.49 km/h, which implies that the average running distance is less than 5 km. Referring to previous studies, this may explain why the running pace of participants may induce insufficient fatigue to impact kinematics of pelvic and knee angles and spatial gait parameters. Consequently, a significant result may occur from a variety of movements as measured by repeating the running gait cycle rather than fatigue (Riley et al., 2007). Though this study did not show significant differences in the lower extremity kinematics, there were general trends in the pelvic and knee kinematics. For example, pelvic anterior/posterior tilt angles at TO (Figure 3a) have similar patterns in intra-individual time points. Nevertheless, there were inter-individual variabilities; a large intra-individual variability in pelvic tilt angle was exhibited in the first two participants (approximately 5°) compared to the ninth participant (approximately 25°). Interestingly, it was observed that both knee flexion angles of all participants presented a similar pattern between time points. The abovementioned factors may explain why the findings did not show significant differences between time points. The findings of this study demonstrate that each runner responds to the time change differently. The running velocity of each individual may also affect changes in the lower extremities' kinematics. Furthermore, the timing of stance and swing phases depends on the variability of each individual between the time points. This may represent the running technique of participants who could control their motions and technique with less altered angle and spatial gait parameters during running on the treadmill. Moreover, this work provides a practical overview of the measurements and interpretation of pelvic and knee running biomechanics and may help to at least identify changes in the pelvic and knee kinematics during 30-min running and provide feedback to improve running performance or reduce injury risk.

Conclusions

The pelvic and knee kinematics at IC and TO were observed in addition to step and stride lengths between four different time points of 30-min running. The main finding was that there was no significant difference with an increase in running time. These findings suggest that each runner responds to the time change differently because the results showed similar patterns in some variables in intra-individual's time points. However, there were inter-individual variabilities across the analyzed variables. Hence, each individual may affect changes to the lower extremities' kinematics in an individual way suggesting subject-specific 'signature' coordination. Coaches, athletes, and sports scientists can use the knowledge of the pelvic and lower extremity biomechanics during running over time to improve training by incorporating similar spatiotemporal characteristics in the drills, rehabilitation, or exercises used to develop the performer. We recommend to observe the lower limb kinematics during running over time to prevent the incidence rates in the running population. Therefore, this study may be beneficial for athletes to reduce injury risk and provides a contribution to the knowledge of the lower extremity mechanics during running at different intensities.

Conflicts of interest - If the authors have any conflicts of interest to declare.

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