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Changes in sagittal plane kinematics with treadmill familiarisation to barefoot running

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Abstract

Interest in barefoot running and research is growing. However a methodological issue surrounding investigations is how familiar the participants are with running barefoot. The aim of the study was to assess the amount of time required for habitually shod runners to become familiar with barefoot treadmill running. Twelve female recreational runners, who were experienced treadmill users, ran barefoot on a treadmill for 3x10 minutes at a self-selected speed, with 5 minute rest periods. Sagittal plane kinematics of the hip, knee, ankle and foot during stance were recorded during the first and last minute of each 10 minute bout. Strong reliability (ICC > 0.8) was shown in most variables, after 20 minutes of running. Additionally, there was a general trend for the smallest standard error of mean to occur during the same period. Furthermore there were no significant differences in any of the biomechanical variables after 20 minutes of running. Together this suggests that familiarisation was achieved between 11 and 20 minutes of running barefoot on a treadmill. Familiarisation was characterised by less plantarflexion and greater knee flexion at touchdown. These results indicate that adequate familiarisation should be given in future studies prior to gait assessment of barefoot treadmill running.

Keywords: Kinematics, reliability, running gait

Word count: 3625

Introduction

Currently there is great interest within the running community in running barefoot (or in shoes mimicking barefoot running), with approximately 75% of American runners interested in it, from both a performance and injury perspective [1]. Consequently, research into barefoot running has typically addressed its potential to enhance performance [2-5] and reduce injury [5-7]. Barefoot running is also utilised as a test condition by many researchers investigating the effect of footwear, even though for many participants it is likely to be the first time they have ever run barefoot. This raises one of the methodological issues surrounding the study of barefoot running i.e. the familiarity of the participants to running barefoot. A lack of familiarity may limit the reliability of data obtained from a barefoot running condition.

Previous investigations assessing overground or treadmill running gait fall into three categories regarding their barefoot/treadmill familiarisation procedures: 1) They fail to report whether any time was given for barefoot or treadmill familiarisation [2-4,8,9]; 2) They state practice barefoot trials [10,11] / treadmill familiarisation [2,12,13] was performed without specifying time; 3) They report familiarisation was achieved when the participant believed they were comfortable with the condition [14-16]. Given that many studies find biomechanical differences between barefoot and shod conditions whilst running (e.g.[11,17,18]), it is possible that some findings may be influenced by initial adjustments made in response to the removal of footwear if inadequate familiarisation was given.

It has been argued that multiple steps need to be accumulated prior to biomechanical analysis of barefoot running [12], so any gait modifications precede the gait assessment. However, the time necessary for runners to become familiar with barefoot running on a treadmill, such that their running kinematics stabilise to an acceptable level during a testing session [19,20], is unknown. Previous research suggested that 8-9 minutes is required for spatio-temporal adjustments whilst running shod on a treadmill [19,21]. A more recent study has demonstrated that kinematic alterations can be made within six minutes of treadmill running [20] and that just 8 seconds is needed for kinetic familiarity [22]. These studies suggest the time taken for shod individuals to adjust to one unfamiliar factor, treadmill running, is within 10 minutes. By using individuals who are already familiar with treadmill running, only one unfamiliar factor exists when assessing barefoot treadmill running. Furthermore barefoot running is often seen as another type of footwear condition by researchers, implying kinematic responses to adjusting to such a test condition may be similar. Therefore it is possible that the length of time required for barefoot familiarisation might be similar to shod running, however this requires specific investigation.

The aim of this study was to assess the amount of time required for habitually shod runners, with previous treadmill running experience, to become familiar with barefoot treadmill running. It was hypothesised that runners would be able to produce a consistent gait pattern within 10 minutes of running barefoot on a treadmill.

Methods

Participants

Twelve female recreational runners (height: 167.7 ± 6.5 cm; mass: 61.4 ± 5.5 kg; age: 24.6 ± 5.4 years; weekly running distance: 70.1 ± 21.9 km; running experience: 8.6 ± 3.7 years) who regularly ran on treadmills volunteered for the study. Regularly running on a treadmill was defined as runners who had run for at least 30 minutes per week on a treadmill for the past 6 months. All participants were free from injury at the time of testing. Only runners who had limited (less than 5 minutes) or no previous experience of barefoot running were included in the study. Thus all participants were classified as beginner barefoot runners. Ethical approval was obtained from the University's Sport and Health Sciences department.

Apparatus

An eight camera Peak Motus motion analysis system (Vicon Peak, 120 Hz, automatic optoelectronic system; Peak Performance Technologies, Inc., Englewood, CO), situated in an oval shape around a treadmill was used to capture 3D kinematic data (120 Hz). The system was calibrated using a wand length of 0.93 m and a fixed volume covering the treadmill belt.

A motorized treadmill (PPS 43med; Woodway, Weilam Rhein, Germany) was used during the running trials. The speed of the treadmill was checked prior to testing by recording the time taken for the treadmill belt to complete four revolutions. This was captured using a Basler camera (100 Hz), which was positioned directly in front of the treadmill, approximately 1.5 m away from the treadmill. The treadmill belt length (3.60 m) was used to calculate the speed of the treadmill belt during four revolutions. This speed was then compared to the digital display on the treadmill monitor. This was completed for speeds ranging from 2.08 to 3.08 $m \cdot s^{-1}$ (mean: 2.58 ± 0.3 $m \cdot s^{-1}$). Based on the standard error of estimate there was 95% confidence that the speed of the treadmill belt was within 0.03 $m \cdot s^{-1}$ of the speed displayed on the monitor.

Marker Placement

Ten spherical reflective markers (diameter: 12 mm) were affixed to the right lower limb of the participant using double-sided adhesive tape. A modified Soutas-Little [23] model was used to include the thigh segment, with markers placed on the following anatomical landmarks: the proximal greater trochanter (hip); the medial and lateral condyles (knee); midline of the posterior shank; the musculotendinous junction where the medial and lateral belly of the gastrocnemius meet the Achilles tendon; the mid-tibia below the belly of the tibialis anterior; the lateral malleolus (ankle); the superior and inferior calcaneus; and the proximal head of the third metatarsal.

To determine stance a triaxial accelerometer (Trigno Wireless EMG, Delsys, Boston, MA, USA), sampling at 148 Hz, was affixed to the right heel of the participant's foot. The vertical component of the accelerometer data was used to detect touchdown (TD) and toe-off (TO), following similar procedures to those used elsewhere [24].

Procedures

Each participant was instructed to self-select a speed which they felt they could comfortably run at for 30 minutes and which was representative of their training speed. They performed a warm-up on the treadmill for 5 minutes at this speed whilst wearing their own, traditional, trainers. Then they ran barefoot at this speed for 3 x 10 minutes, with 5 minute rest periods in between each bout. This amount of time was chosen based on previous treadmill familiarisation studies [19-21]. As barefoot running could potentially cause discomfort during initial runs the protocol included rest periods to decrease the continuous time performing an unfamiliar task. No verbal instructions were given to the participants with regards to running technique throughout the testing period.

Data were captured in the first and last minute of each bout of 10 minutes, with the data being recorded during the first minute approximately 10 s after the treadmill had reached the required speed. This resulted in six time points: 1st minute (T1), 10th minute (T2), 11th minute (T3), 20th minute (T4), 21st minute (T5) and 30th minute (T6). Six complete, consecutive running cycles were collected during each recording with only data during the stance period used for further analysis due to loss of data, particularly of the shank, during the swing phase.

Data reduction

The coordinate data of the right leg were smoothed within the Peak Motus software using a quintic spline smoothing technique. Further analysis occurred through a customized MatLab (Math Works Inc., Cambridge, MA, USA) script. The accelerometer data, which was simultaneously recorded alongside the kinematics, was resampled to match the kinematic data collection frequency. Sagittal plane kinematics have the greatest reliability compared to the transverse and frontal planes [25,26]. Therefore only sagittal plane movements were analysed. The hip angle was defined as the angle between the thigh segment and the vertical line through the hip marker. The knee angle was defined between the thigh and shank segments and the ankle angle defined between the shank and foot segments. The foot angle was defined as the angle between the ground and the vector created between the inferior calcaneus and the proximal head of the third metatarsal [27]. In addition to the running data, a standing trial was recorded. This was performed in the anatomical position and the standing trial angles were subtracted from the experimental data to provide anatomically meaningful angles.

Positive values represent hip extension, knee flexion and ankle plantarflexion. The angles at TD and TO were calculated for the hip, knee and ankle, and foot angle at TD was used to detect footstrike patterns [27]. Additionally, the hip angle at 50% of stance (midstance) and the peak flexion during stance for both the knee and ankle were determined. Stride length was calculated using the following formula:

$$SL = V \, x \, ST$$

SL = stride length. V = velocity of treadmill. ST = stride time (the time taken between successive contacts of the right foot) [21].

Statistical analysis

Means were computed at each time point (T1, T2, T3, T4, T5 and T6), using the six gait cycles recorded at that time point. Sharipo-Wilk tests were performed on these means to test for normality and all were normally distributed. All within-subject reliability tests of the dependent variables were calculated with these means. First, intraclass correlation coefficients (ICC) between consecutive time points (T1-T2, T2-T3, T3-T4, T4-T5 and T5-T6) were established using the means calculated. Secondly, using the same means the standard error of means (SEM) was computed, both in absolute and relative terms. Finally, a one-way repeated measures ANOVA was used to determine if there were any within-subject significant differences in each dependent variable across the time points, with T-tests used for post-hoc comparisons (Fisher's LSD). Statistical significance was set at $p \leq 0.05$ and all statistical tests were performed using SPSS version 19 (SPSS Inc., Chicago, IL).

Results

The intraclass correlations indicated that the highest reliability was found in the last 10 minute cycle of barefoot running. All variables except knee flexion at TD showed strong reliability (ICC > 0.8) after 20 minutes of running. Moderate reliability (ICC: 0.6 - 0.8) was shown for all variables after 10 minutes of running barefoot. The most consistent kinematics (ICC > 0.8) throughout the whole run were: foot at TD; dorsiflexion at TD; hip at TD; hip at midstance; hip at TO and peak knee flexion. Additionally stride length was found to have the highest ICC at each time period during the 30 minutes.

There was a general trend for the smallest SEM, both in relative and absolute terms, to be found after 20 minutes of running. The only exceptions to this were the peak knee flexion and the hip at TD (Table 1), whereby the smallest SEMs were recorded during the first 10 minutes. However the relative SEMs were always below 10% for both variables, suggesting that these were the most reliable kinematics throughout the whole run.

There were four kinematic variables (out of 13) that were significantly different across time periods (Figure 1): dorsiflexion at TD; knee flexion at TD; knee flexion at TO; and hip angle at TO. Post hoc analysis revealed that there were no significant differences after T4, suggesting that the kinematic variables were stable after 20 minutes of running barefoot. No significant differences were observed in the other kinematic variables or the stride length.

In light of the change in ankle angle and unchanged foot angle, the tibia would need to be rotated further forward after the 20^{th} minute, rather than the foot being placed flatter to the ground. To test this hypothesis further analysis was performed on the data to see if there was a significant change in the position of the shank segment relative to the vertical at TD. This was performed using a one-way repeated measures ANOVA, with the shank angle at TD as the dependent variable, followed by post-hoc T-tests (Fishers' LSD). Results revealed a significant increase (19.9%; $p = 0.022$) in the shank angle with the vertical at TD from T1 to T4 (11.9 vs. 14.2 °, respectively). Furthermore, there were no significant changes after 20 minutes.

Discussion

This study investigated the time required for habitually shod runners to become familiar with barefoot treadmill running. The results show that kinematic familiarisation occurred between 11 and 20 minutes of running, thus contradicting the study hypothesis that less than 10 minutes would be required. There were no significant differences in any of the biomechanical variables after 20 minutes (T1 to T4), suggesting that the runners were able to produce a consistent gait pattern following this period of time. Furthermore, all but one of the variables measured were found to have strong reliability, based on ICC values, between 20-21 minutes and 21-30 minutes. Additionally, the smallest SEMs were found during the same time periods.

Previous studies have reported that less time is required to become familiar with shod treadmill running, in the region of 6-9 minutes [19-21]. However it is likely that the participants in these studies were habitual shod runners, meaning they only had to adjust to the movement of the treadmill. The current study results suggest that adjusting to the lack of footwear requires more time and is perhaps more complex than only adjusting to the movement of a treadmill. The results also highlight that researchers need to give participants appropriate familiarisation time before using barefoot running as a test condition. This is due to the initial adjustments that participants may be making to the lack of footwear, which for most is an unfamiliar feeling.

Part of this unfamiliar feeling when running barefoot stems from the heightened somatosensory feedback that runners feel due to the lack of an external cushioning layer [28-30]. Such a layer insulates the foot from its own sensory feedback that helps govern the impact during ground contact [28,31]. It is argued that gait adjustments made during barefoot running attenuate mechanical stresses placed upon the feet [28], but the current findings suggest that such modifications to a runner's gait are not instantaneous. It is also conceivable that the reduced variability in running mechanics could be a result of increased muscular fatigue and/or lower limb soreness that would take time to develop. Whilst this study is unable to attribute the reduced variability in running mechanics to a specific mechanism, based on the findings, it can be advised that adequate familiarisation of between 11 and 20 minutes should be given to habitually shod runners prior to testing barefoot treadmill running.

The variation (represented by the SD), particularly at the ankle angle during initial ground contact (Figure 1a), could suggest that even though the mean for each kinematic adjustment tended to plateau between 20 and 30 minutes (T4 and T6), there was still large intra-individual variation during this time period. However Figure 2 indicates that this is not the case. The variation demonstrated was a result of large inter-individual differences in ankle angle at TD, rather than intra-individual differences. The lack of intra-individual differences suggests that runners were able to perform a consistent gait pattern, hence were familiarised with barefoot treadmill running, within 20 minutes of running.

As well as providing evidence regarding the time taken to adjust to barefoot running, the current study highlights some interesting specific gait adjustments made from the first minute to the 20th minute. Firstly, runners adopted less plantarflexion (or more dorsiflexion) following the 20th minute familiarisation (2.86 vs. -0.61°, T1 vs. T4 respectively). Initially 9 runners had at least 1° or more of plantarflexion at TD compared to after 20 minutes when only 3 runners exhibited plantarflexion. This suggests that some of the previously reported TD ankle angles, showing more plantarflexion when barefoot compared to shod, [2,11] could be a result of unfamiliarity with barefoot running. It has been argued that such gait alterations reduced high loads at the heel by increasing the contact area of the heel through a flatter foot at impact [2,11]. However the current study has demonstrated that this may be a natural response to running barefoot for the first time and could be a result of inadequate familiarisation. As recent evidence has shown that a flatter foot placement reduces the peak heel pressures [32], the fact that foot angle did not change during the familiarisation period, contradicting Squadrone and Gallozzi [2] and de Wit and colleagues [11], suggests that there was no increase in contact area to disperse the impact load. Other kinematic changes could help explain the cushioning characteristics of barefoot running.

The initial average foot angle during familiarisation suggested that, generally, runners were midfoot striking during both the 1st (4.37°) and 20th minute (5.41°) [22]. Based on the classification of Altman and Davis [27] (forefoot striking: foot angle $< -1.6°$; rearfoot striking: foot angle $> 8°$; midfoot striking: $-1.6° <$ foot angle $< 8°$) there were 3 forefoot strikers, 5 midfoot strikers and 4 rearfoot strikers. Whilst foot angle remained similar across the different time points, there were changes in the shank angle relative to the vertical. This tibial movement would explain the greater knee flexion recorded at TD with increased running familiarity, consistent with the hip angle at TD being similar across each time point. Previous research has reported either greater knee flexion at TD when running barefoot compared to running shod [11,33] or no difference between the two conditions [2]. However, the current findings suggest adequate familiarisation allows runners to produce even greater knee flexion at TD meaning previous differences found may be smaller than what could have been achieved with familiarisation. Furthermore de Wit and colleagues calculated that 96% of the variance in foot angle at TD could be determined by the ankle angle and shank angle during barefoot running [11], showing how intrinsically linked these positional angles are. Therefore, it appears that with increased familiarity runners utilise the knee to a greater degree to help attenuate the impact by reducing their effective mass

[34]. By adopting a more flexed knee at TD the magnitude of impact force experienced could be reduced [35], possibly reducing the likelihood of injury [36]. So rather than producing a flatter foot, increasing the amount of contact area to lower the loads experienced, it seems that runners tended to change their knee and shank positions to possibly facilitate a reduction of impact force.

Stride length was the most reliable gait characteristic with little variation over time, meaning runners adjusted their stride length almost instantaneously at the beginning of the run. Therefore it is likely that the shorter stride lengths reported during barefoot running [2,5,11] may be an anticipatory strategy, such as that used when adjusting leg stiffness in response to changes in surface [37]. This strategy would be controlled by visual cues of the surface, knowledge of the surface properties from previous experiences [37], and heightened somatosensory feedback whilst standing on the surface prior to running on it, due to the lack of an external layer between the foot and surface. Previous results have shown that even a small layer between the foot and the surface that lessens somatosensory feedback, such as a minimalist shoe, means runners choose a similar stride length to that demonstrated during shod running [2]. For such a stride length to be consistently reproducible during shod running on a treadmill may take between 2-4 minutes [20]. Conversely by removing the external layers that insulate the foot from impact with the ground, runners are able to adopt consistent stride lengths almost immediately. It is important to note, that although the results show stride length to be adopted instantaneously, we cannot discern whether these stride lengths were different to the habitual shod stride lengths of the runners.

Due to this heightened somatosensory feedback when running barefoot the interaction between the surface and the foot should play a greater role in determining the running mechanics of an individual. Elements known to affect a runner's gait, such as surface stiffness [37,38], could influence the time to familiarisation. The same treadmill was used throughout testing to minimise the effect the surface could have on time to familiarisation, but caution should be exercised when generalising these findings to other treadmills and overground running with different surface properties. Nevertheless, the results support the argument made by Divert et al., [12] that multiple steps need to be accumulated prior to assessing the biomechanics of barefoot running. Therefore it is not unreasonable to suggest that numerous practice trials should be given in barefoot overground running conditions prior to experimental testing. However, further research is needed to assess the time/number of trials required.

It is possible that familiarisation may have occurred sooner than 20 minutes if no rest period was given. However this protocol was deemed necessary following pilot work, which tested 30 minutes of continuous running and found this caused soreness in the lower limb during and post-exercise. For this reason, researchers should be cautious about familiarising participants to barefoot treadmill running the same day as their experimental testing. Whilst slight alterations to running mechanics may occur in the initial few minutes of treadmill running performed on separate days, providing runners with adequate familiarisation to treadmill running on a separate day, prior to testing, has been shown to reduce these alterations to running mechanics [19]. Additionally, familiarisation could have occurred at any point between 11 and 20 minutes. However, due to data being collected at the beginning and end of each bout, the exact time of familiarisation cannot be identified. Further investigations, which record data more frequently, are needed to ascertain the exact minute adequate familiarisation was achieved.

In conclusion, to familiarise habitually shod, experienced treadmill runners to barefoot treadmill running, 11 to 20 minutes of running on a treadmill should be given in one session. Kinematic and spatio-temporal measures were consistent and stable within 20 minutes, suggesting that future studies should include a sufficient period of familiarisation to barefoot running prior to commencing experimentation. After familiarisation, runners adopted less plantarflexion and greater knee flexion during initial ground contact. However stride length changes during barefoot running were adopted immediately.

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Figure 1. Kinematic changes over time. a) Ankle at TD. b) Knee at TD. c) Knee at TO. d) Hip at TO. TD = touchdown. TO = toe-off.

Figure 2. Individual ankle angles at TD across each time point (grey lines). The mean values for each time point is represented by the black line (±SD). TD = touchdown.

Table 1. Absolute (relative) standard error of means (SEM) of the sagittal plane kinematics and stride length

Variable	Time periods				
	T1-T2	T2-T3	T3-T4	T4-T5	T5-T6
Foot angle TD[a]	1.20	1.82	1.63	1.41	0.99
Dorsiflexion TD[a]	2.87	2.55	2.03	1.82	1.19
Dorsiflexion peak	2.33 (17.5%)	4.35 (32.2%)	2.26 (18.1%)	1.12 (9.2%)	1.78 (14.5%)
Dorsiflexion TO[a]	7.17	7.15	3.33	2.71	2.10
Knee flexion TD	3.21 (30.6%)	2.00 (19.5%)	2.19 (19.6%)	2.22 (18.0%)	1.92 (15.2%)
Knee flexion peak	1.48 (4.0%)	2.81 (7.7%)	2.61 (7.2%)	2.72 (7.4%)	1.66 (4.4%)
Knee flexion TO	2.34 (18.2%)	1.52 (12.8%)	1.66 (13.4%)	1.46 (12.2%)	1.16 (9.8%)
Hip TD	0.59 (2.8%)	0.77 (3.8%)	0.91 (4.5%)	1.29 (6.3%)	0.69 (3.3%)
Hip midstance	1.63 (13.7%)	1.19 (10.0%)	1.07 (8.8%)	1.20 (10.2%)	0.80 (7.0%)
Hip TO	1.89 (10.3%)	1.96 (10.2%)	1.65 (9.0%)	1.39 (7.6%)	1.18 (6.2%)
Stride length	0.04 (1.7%)	0.04 (1.7%)	0.02 (1.0%)	0.02 (0.6%)	0.02 (0.6%)

[a] Relative standard error of mean was not calculated due to the variation in kinematic values around zero. T1 = 1st minute. T2 = 10th minute. T3 = 11th minute. T4 = 20th minute. T5 = 21st minute. T6 = 30th minute. TD = touchdown. TO = toe-off.

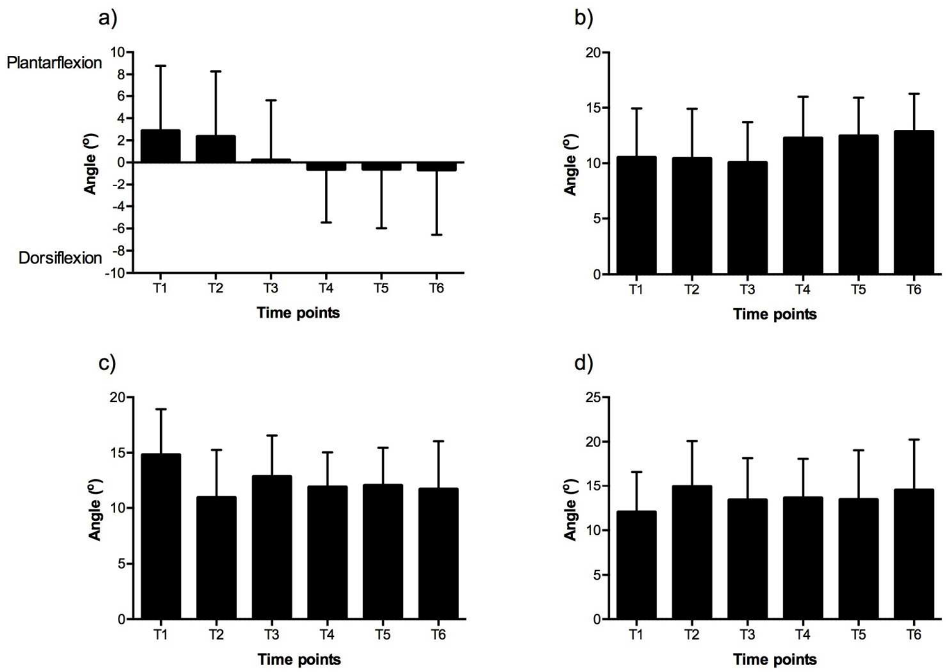

Figure 1. Kinematic changes over time. a) Ankle at TD. b) Knee at TD. c) Knee at TO. d) Hip at TO. TD = touchdown. TO = toe-off.
178x124mm (300 x 300 DPI)

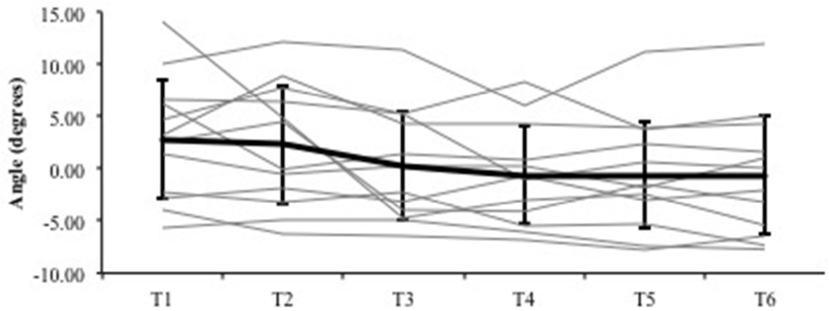

Figure 2. Individual ankle angles at TD across each time point (grey lines). The mean values for each time point is represented by the black line (±SD). TD = touchdown.
146x57mm (72 x 72 DPI)