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Analysis of Segmental Coordination in the Lower Extremity using Vector Coding: A Pilot Return-to-Play Study of Acute Ankle Sprain

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Abstract

Background: Acute ankle sprain may affect ankle function during sport and daily activities. This study aimed to use vector coding technique to analyze the difference over time between injured and healthy lower limb during the first week of acute ankle sprain phase (P1) and post a 1-month recovery phase (P2) to understand the return-to-play coordination strategy in the lower extremity. **Methods:** Six females attended the gait experiments with attached 40 reflective markers using eight-camera Vicon motion capture system. All participants walked barefoot while turning in four directions (T0°, T45°, T90°, T135°) at their self-selected speed. Coordination patterns were classified as in-phase, anti-phase, proximal or distal dominancy between lower limb joints involving hip, knee, ankle, subtalar, metatarsophalangeal (MTP) joint and tarsometatarsal (TMT) joint. **Results:** P1 showed more proximal joint dominant in Hip-Knee coupling angles but P2 displayed more distal joint dominant in Knee-Ankle joint coordination pattern and mainly distal joint dominant in Ankle-MTP coupling angle mapping. The Ankle-TMT1 and Ankle-TMT5 coordination patterns matched best in straight walking but worst in T135 walking. **Conclusions:** Investigating inter-segmental coordination in different turning movements could provide insights into gait changes from acute ankle sprain from one-month return-to-play recovery. Knowledge of lower limb coordination pattern may provide clinical implications to improve dynamic balance and gait stability for individuals with acute ankle sprain.

Keywords: Acute ankle sprain, Turning, Coordination pattern, Kinematics, Gait

Introduction

Ankle injuries were commonly reported in athletes and physically active populations [11], with ankle sprain taking up to 85% [22]. Studies showed that about 80% would suffer an ankle sprain during lifetime [17],[29]. Moreover, the probability of ankle sprain was different in various sex, age and sport-playing groups. Comparing with males, ankle sprain was more common in females. Children were more susceptible to ankle sprain than adults, as well as court sports, especially in-door sports had a higher incidence of ankle sprain than any other sports activities [3],[10],[32]. With society placed more emphasis on exercise and physical activity, more people participated physical exercise, reporting an increased incidence of ankle sprain. Therefore, it was extremely necessary to understand the ankle sprain and the following up return-to-sport strategy.

The acute ankle sprain had great impact on individuals' daily life. Specifically, the high cost of diagnosis and treatment in the healthcare system, and the economic loss due to emergent absence from acute ankle sprain were reported [10]. Without proper treatments, it may develop chronic ankle instability [27], which may affect the level of physical activity and reduce the quality of life [18],[19]. Gait was the most frequent daily activity [21]. A normal gait cycle was crucial for returning to physical activity and work, as well as for predicting potential features of recurrent ankle sprain [26]. In order to develop proper rehabilitation and recovery practices, gait biomechanics of acute ankle sprain was investigated in this study.

Previous studies reported the kinematic and kinetic changes during gait in acute ankle sprain patients, which was noted that dorsiflexion was considered a risk factor for ankle sprain reinjury [4],[13]. Crosbie et al. measured the range of dorsiflexion and the time of gait in 34 patients recovering from ankle sprain, and found that the degree of dorsiflexion decreased and walking speed decreased in ankle sprain patients [9]. Joint range of motion (ROM) measurements were performed in 28 patients at the emergency department on day 4 and day 30 of acute ankle sprain, showing that the complete recovery lasted one month after injury, but reduced ROM was associated with sports function and quality of life after injury [1]. By comparing 30 patients with grade I and II acute ankle sprains after 4 weeks with 15 healthy individuals, it was found that the step length was shorter during walking, the single support time was shorter, the muscle strength was reduced, the maximum plantar flexion was delayed in gait cycle, and the maximum moment was decreased [26].

Previous studies had described chronic ankle instability (CAI), copers, and healthy individuals [33],[34]. However, few information about the segmental coordination of acute ankle sprain return-to- sport during gait was reported in detail. In gait analysis, changes in the rotation of lower limb joints over temporal series had been widely used in reporting and evaluating foot movements, but these were all analyzed in isolation. Thus, it was difficult to observe kinematic interactions between adjacent segments of lower limb. A vector coding technique solved this problem by providing a simple expression to understand the coordination pattern between adjacent segments of lower limb [30]. The technique was previously applied to analyze walking and running gait. Michael et al. used the seven-camera ProReflex system to test 12 participants at one walking speed and three running speeds to determine three-dimensional joint kinematics through cross-correlation [25]. Vector coding techniques were used to identify coordination patterns between calcaneus, midfoot, metatarsus of foot kinematics during walking [2]. In addition, previous studies also reported that the classification of different coordination patterns during walking [5],[8],[31]. The findings of these studies demonstrated that this technique could be applied to gait analysis, whilst the coordination patterns between acute ankle sprain and return-to-play were not comprehensively investigated. Moreover, the coordination pattern of joint rotation in the lower extremities between different joints, such as hip, knee, were not investigated in the recovery phase of acute ankle sprain.

The objective of this study was to identify the coordination pattern of lower limb joints during walking and turning movements of ankle sprain using a vector coding method. Findings may facilitate the visualization and highlight the clinical significance of coordination patterns of lower extremity and foot-ankle complex for the treatment and recovery of acute ankle injuries.

Materials and Method

Participant

Data collected from six female participants within first week of their acute ankle sprain phase (P1) and a 1-month recovery phase (P2) [1] were used for the analysis. Participants (age: 21±2.16yrs, height: 164±4.82cm, mass: 51±5.88kg) had no history of lower extremity fracture or surgery, acute or chronic lower extremity musculoskeletal sprain within 6 years prior to the experiment, or other known pathologic effects on gait. Six female participants without any exercise therapy provided informed consent before the experiment, and the protocol was sought and approved by the University's Human Ethics Committee (RAGH20210717).

Experimental protocol

An eight-camera motion capture system (Oxford Metrics Ltd., Oxford, UK) was used for kinematic data collection at 200 Hz, for the analysis of hip, knee, and ankle joint kinematics during gait. An in-ground force platform (AMTI, Watertown, MA, USA) was used for GRF collection at 1000Hz. The multi-segment foot model (Figure1_i) used in this study was 40 marker-set (diameter: 12 mm), including left and right shoulder and lower limb, specifically Acromium, Anterior superior spine, Posterior superior iliac spine, KneeMed, KneeLat, AnkleLat, AnkleMed, Heel, Midfoot, Forefoot, Digits, as well as tracking clusters on the thigh and shank.

All participants were informed of the experimental procedure and requirements. After warming up for 10 minutes, participants walked to the force plate with barefoot from a distance of five meter at self-selected speed. All participants were asked to walk in straight (T0), turning 45 degrees (T45), turning 90 degrees (T90), and turning 135 degrees (T135) (Figure1_ii). One static trail and three dynamic trials of each participant were collected in the study. The test was divided into two phases: one was within first week of the acute ankle sprain phase (P1); the other was one month after the first test (P2). If the participants had any discomfort at the injured limb during the experiment, the experiment could be terminated at any time.

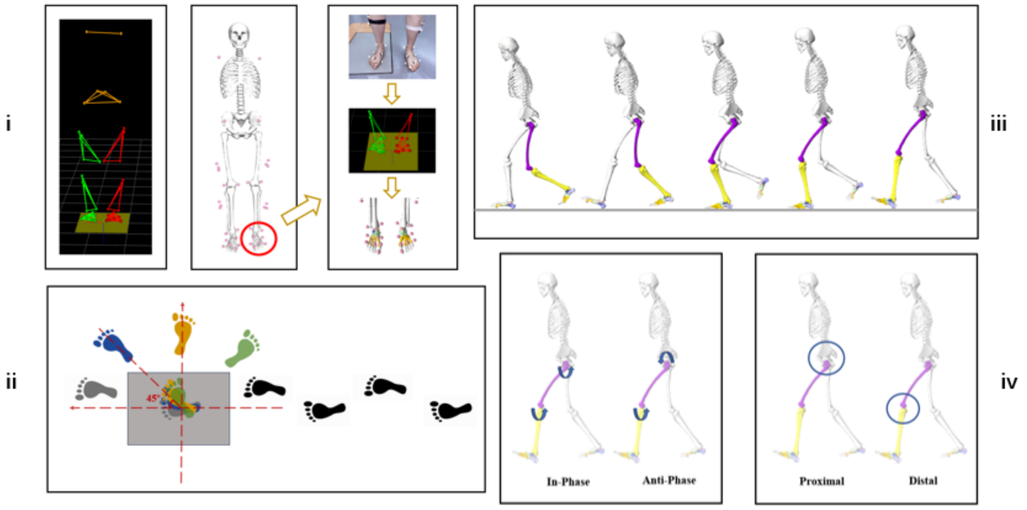

Figure 1. The location of the markers attached on the participant of acute ankle sprain (i).; Experimental setup and of acute ankle sprain in gait (ii); The stance phase of the gait from touch-down to toe-off in this study (iii); Identify four coordination patterns of stance phase during walking, e.g. hip and knee (iv).

Data processing

This study used the modified KULeuven_8DoF model [23] to process data based on the pipeline established by OpenSim (v4.2). In this study, the analysis phase of gait was divided into the part of the participant walking on the in-ground force platform (touch-down) to off the in-ground force platform (toe-off), which was the stance phase (Figure1_iii). After normalizing the stance phase into 101 times frames, the model was scaled by the static label position of each participant to achieve a matching motion model, and the lower limb joint angle was calculated using the inverse kinematics (IK) algorithm.

Statistical analysis

The data was analyzed using a modified vector coding technique [5]. The coupling angle was defined into four categories, reflecting the pattern of coordination between joints: in-phase (adjacent joints rotate in same directions), anti-phase (adjacent joints rotate in opposite directions), proximal phase (proximal joint rotation is dominant), and distal phase (distal joint rotation is dominant) (Figure_1iv). Coordination is obtained by inferencing the coupling angle (0° ≤γ≤ 360°), which is a vector relative to two contiguous time points adjacent to the right horizontal direction [15], [16]:

$$\gamma_{j,i} = tan^{-1}(\frac{y_{j,i+1}-y_{j,1}}{x_{j,i+1}-x_{j,i}}) \tag{1}$$

The mean coupling angle (γ_i) is calculated using circular statistics because angles were directional. i was the percentage stance phase of trial of jth [14]. Calculate the coupling angle (γ_i) from the mean horizontal (x_i) and vertical (y_i) components of each percentage of stance phase:

$$\bar{x}_i=\frac{1}{n}\sum_{j=1}^{n}(cos\gamma_{j,1}) \tag{2}$$

$$\bar{y}_i = \frac{1}{n}\sum_{j=1}^{n}(sin\gamma_{j,i}) \tag{3}$$

$$\bar{\gamma}_i = \begin{cases} \arctan(\bar{y}_i/\bar{x}_i) & \text{if } \bar{x} > 0 \\ 180 + \arctan(\bar{y}_i/\bar{x}_i) & \text{if } \bar{x} < 0 \end{cases} \tag{4}$$

Color maps (a) were used to show the calculated percentage of each coordination pattern of the lower limbs in the three planes to understand the most dominant coordination pattern of hip, knee, ankle, subtalar, metatarsophalangeal (MTP) joints, tarsometatarsal (TMT) joints during walking. Adjacent joint angles with mean of lower limb were demonstrated in b of each figure. The d and e were six participant trails of coordination pattern. The time-varying coupling angle during P1 and P2 was analyzed using paired-sample t test in the open-source SPM package (c) with significance threshold of P=0.05. MATLAB (R2019a, Mathworks, MA, USA) was used to complete all calculations.

According to Chang et al. [5], the stance phase was divided into three stages: early phase (1-33%), mid phase (34-66%), and late phase (67-100%). The number of frames for four coordination patterns was determined as three stages. Descriptive statistics were calculated for the duration of each coordination pattern in each stage.

Results

The main results included Hip-Knee, Knee-Ankle, Ankle-MPT coupling angles, kinematics joint angles, SPM, individual trails in the sagittal plane and subtalar-TMT1, subtalar-TMT5 in the frontal plane, as well as the other results were included in the Supplementary document.

Sagittal Hip-Knee Coordination Pattern

Figure2_i showed hip-knee mean coupling angles during walking when participants walked in straight. From beginning to 50% of stance phase, mean hip-knee coordination pattern between P1 and P2 were similar. Sagittal plane hip-knee coordination was generally in-phase with hip joint (proximal l dominancy) during early phase of stance while this coordination was entirely anti-phase with hip joint (proximal dominancy) in the sagittal plane. Mean hip-knee coordination changed from hip joint (proximal dominancy) to knee joint (distal dominancy) throughout late phase of stance (Figure2_i_a). Kinematic joint angles of acute ankle sprain had significantly less hip extension and more knee extension than over a 1-month period from 54% to 52% ($p = 0.05$) of the stance phase (Figure2_i_b,c). Individuals trials of participant 1 was similar with participant 2 of straight walking except trials 3(Figure2_i_d,e).

The coordination pattern of sagittal hip and knee motion between acute ankle sprain and over a 1-month period phase was presented in Figure2_ii. Coupling angles was in-phase from the beginning until 50% during T45 walking. Coordination pattern of P1 was similar with P2 between 25% and 50% of stance. Sagittal plane of hip-knee coordination pattern was mainly hip joint (proximal dominancy) in early and middle phase, but in late phase, it was mostly knee joint (distal dominancy) (Figure2_ii_a). Sagittal joint angles had significant difference from 25% to 28% ($P=0.05$) during stance (Figure2_ii_b, c). Individuals trials of participant 1 was similar with participant 2 with T45 walking (Figure2_ii_d,e).

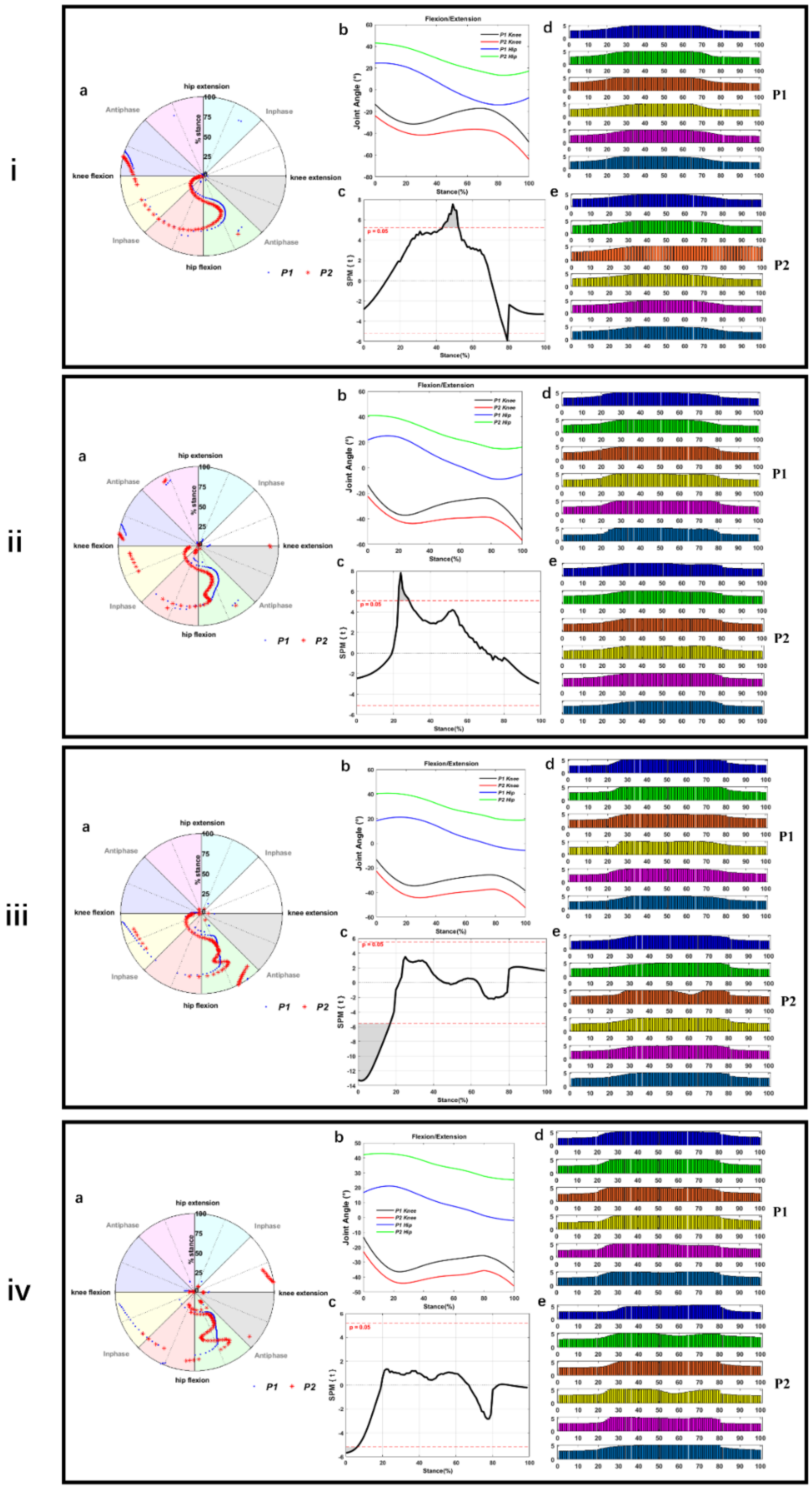

Figure 2. Mapping for hip-knee coordination pattern (a) of injured lower limb between acute ankle sprain phase (P1) and 1-month recovery phase (P2); Comparison of hip and knee joint angles with T0 (ib), T45 (iib), T90 (iib), T135 (ivb); SPM1d analysis (c) of hip and knee joint in gait; Individuals trials of hip-knee coordination in the sagittal plane, respectively for six participants during stance phase of walking (d, e).

Coupling angles of hip-knee joint with T90 walking was displayed in Figure2_iii. The hip-knee coordination pattern was similar from the beginning to the 25% of the stance, which was in-phase in the early phase. In mid and late phase, coupling angle was considerably hip joint (proximal dominancy) (Figure2_iii_a). Joint angles of hip and knee had remarkable different in the sagittal plane between 0% and 10% ($P=0.05$), as well as 58% and 62% (Figure2_iii_b,c). hip-knee joint individuals trials of participant 1 was similar with participant 2 during T90 walking in comparison (Figure2_iii_d,e).

Sagittal coordination variability of hip-knee withT135 walking was showed in Figure2_iv. The hip-knee coordination was dissimilar between P1 and P2, although mostly was hip joint (proximal dominancy) in the early, middle and late phase (Figure2_iv_a). Angles of hip and knee joint had no dominantly difference during the stance of T135 walking (Figure2_iv_b,c). There was a resemblance to individuals trials of mean hip-knee coordination, respectively P1 and P2 (Figure2_iv_d,e).

In addition, hip-knee coordination pattern of uninjured lower limb with straight walking was observed in Figure S1. Coupling angle was similar between P1 and P2, which was in-phase during early phase, and then hip joint (proximal dominancy) in the middle phase. In the late phase of T0 walking was knee joint (distal dominancy) (Figure S1_a). The joint angles, SPM statistical analysis presented no significant difference during stance of straight walking (Figure S1_b,c). The individuals trials of six participants also displayed no difference (Figure S1_d,e).

Mapping for hip-knee coordination pattern of injured and uninjured lower limb in the frontal plane was displayed in Figure S2 and Figure S3 during stance phase of walking. Furthermore, Figure S4 and Figure S5 showed double lower limb of hip-knee coordination in the transverse plane.

Sagittal Knee-Ankle Coordination Pattern

As shown in Figure 3, the coordination patterns of knee-ankle with T0 and T135 walking were observed. Coupling angle was anti-phase of P1 and P2 before 25% of stance. However, coupling angles of P1 was in-phase with knee joint (proximal dominancy) while coupling angles of P2 was in-phase with ankle joint (distal dominancy) from 25% to 100% of straight walking (Figure 3_i_a). Kinematic of knee-ankle joint angles in the sagittal plane presented outstanding difference from 45% to 55% ($P=0.05$), which was the middle phase of stance (Figure 3_i_b,c). Individuals trials of P1 and P2 was observed no difference (Figure 3_i_d,e).

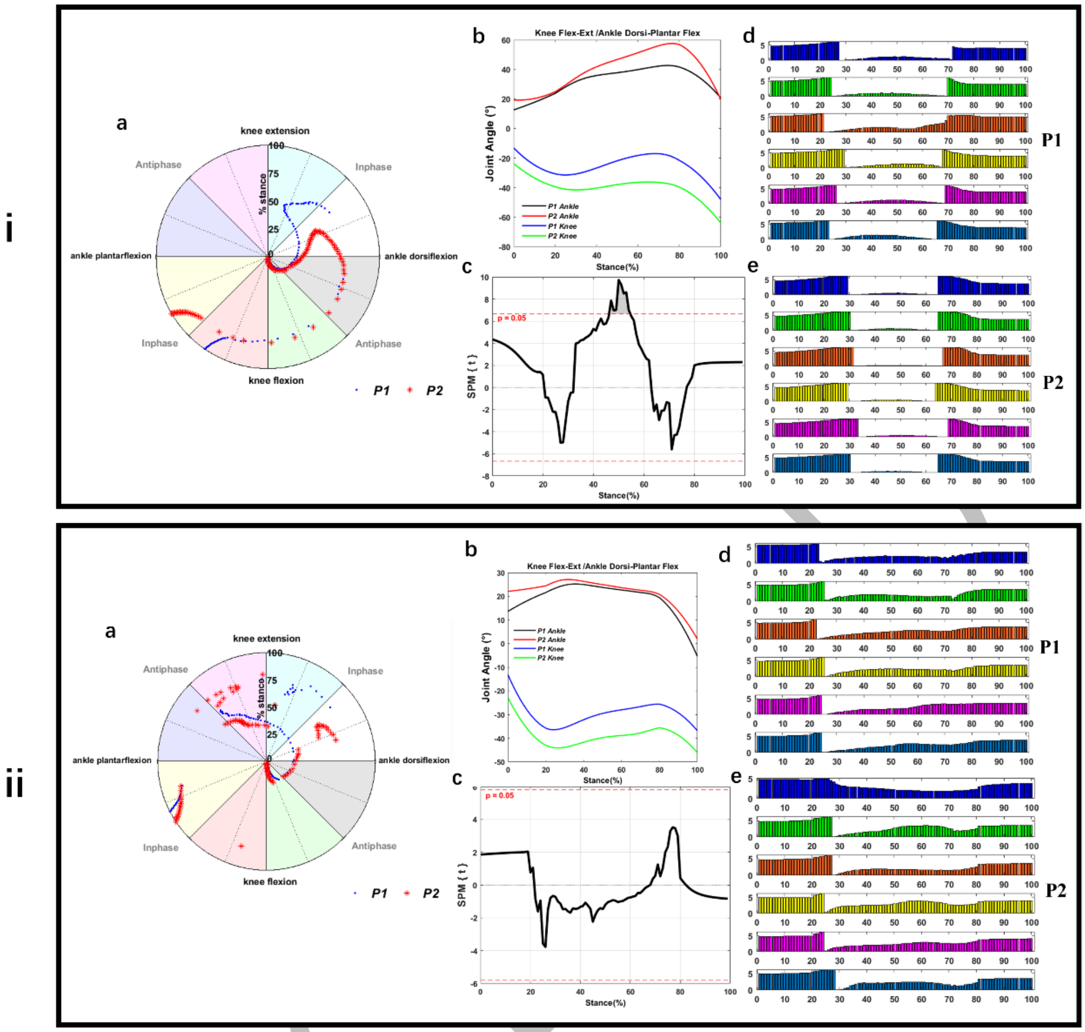

Figure 3. Mapping for knee-ankle coordination pattern (a) of injured lower limb between acute ankle sprain phase (P1) and 1-month recovery phase (P2); Comparison of knee and ankle joint angles with T0 (ib), T135 (iib); SPM1d analysis (c) of knee and ankle joint in gait; Individuals trials of hip-knee coordination in the sagittal plane, respectively for six participants during stance phase of walking (d, e).

Additionally, for T135 walking, the knee-ankle coordination patterns of P1 and P2 were resemble until 25%. Both of them were all anti-phase with knee joint (proximal dominancy) throughout 25% to 50%. After that, P1 was in-phase knee joint (proximal dominancy) but P2 was in-phase ankle joint (distal dominancy). In the late phase, their coupling angels were in-phase ankle joint (distal dominancy) (Figure 3_ii_a).There was no significant difference between joint angles (Figure 3_ii_b,c), six trials of P1 (Figure 3_ii_d) as well as six trials of P2 (Figure 3_ii_e).The rest of T45 and T90 walking in the sagittal plane were demonstrated in FigureS6, which was about coupling angles mapping of knee-ankle coordination pattern in injured lower limb. Coordination pattern of knee-ankle coupling angle in uninjured lower limb was showed was in Figure S7. Figure S8 and Figure S9 displayed coupling angle mapping for knee-subtalar in lower limbs in the frontal plane.

Sagittal Ankle-MTP Coordination Pattern

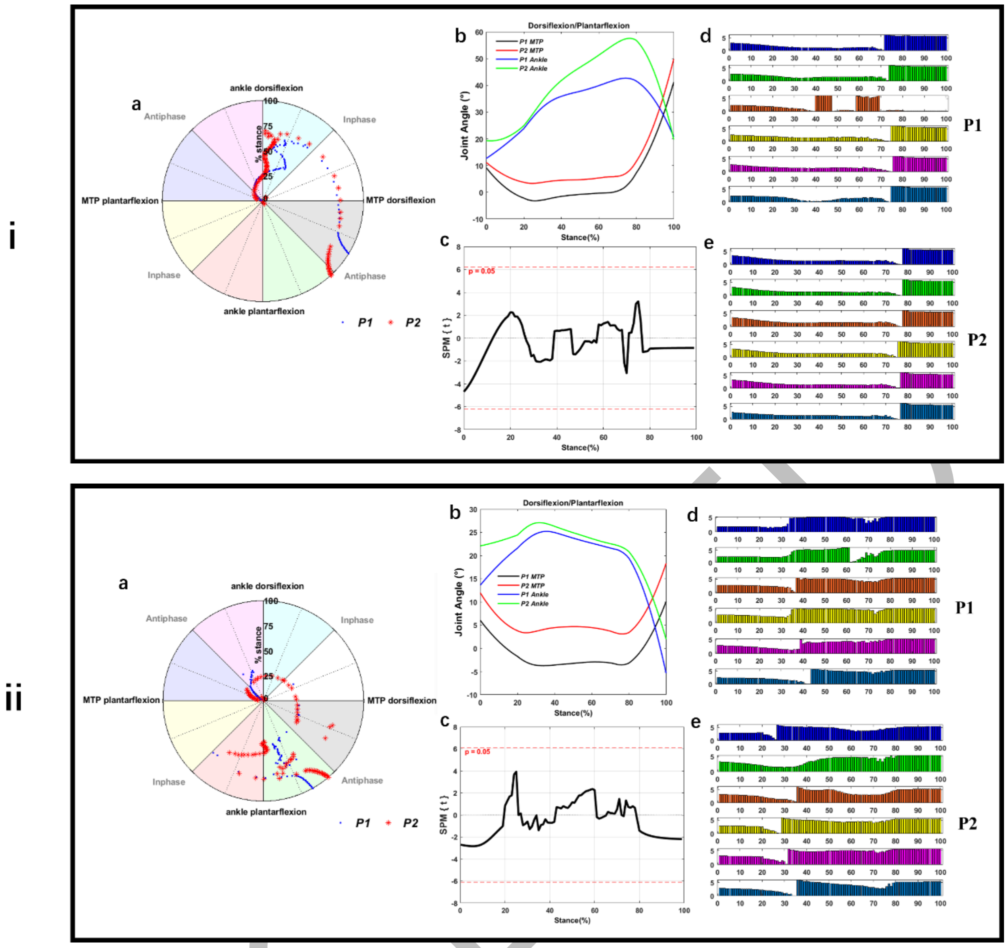

Figure 4. Mapping for ankle-MTP coordination pattern (a) of injured lower limb between acute ankle sprain phase (P1) and 1-month recovery phase (P2); Comparison of ankle and MTP joint angles with T0 (ib), T135 (iib); SPM1d analysis (c) of ankle and MTP joint in gait; Individuals trials of hip-knee coordination in the sagittal plane, respectively for six participants during stance phase of walking (d, e).

Figure 4 suggested coupling angle mapping of sagittal Ankle-MTP. The coordination pattern was anti-phase from 0% to 25%, and then it was in-phase with ankle joint (proximal dominancy) during middle phase of stance. In the walking late phase, the coupling angles was MTP joint (distal dominancy) (Figure 4_i_a). Ankle and MTP joint angles revealed no obvious difference (Figure 4_i_b,c). As for individuals' trials, Figure 4_i_d and Figure 4_i_e was not different besides the third trials of P1 with T0 walking. Moreover, ankle-MTP coordination pattern with T135 walking was mostly MTP joint (distal dominancy), but in the late phase, it was mainly ankle joint (proximal dominancy) (Figure 4_ii_a). There was no distinct difference for joint angles (Figure 4_ii_b,c)and across individual participants (Figure 4_ii_d,e).The coordination pattern of injured limb in T45 and 90 walking and uninjured limb with four directions turning were indicated in Figure S10 and Figure S11, respectively.

Frontal Subtalar-TMT1 Coordination Pattern

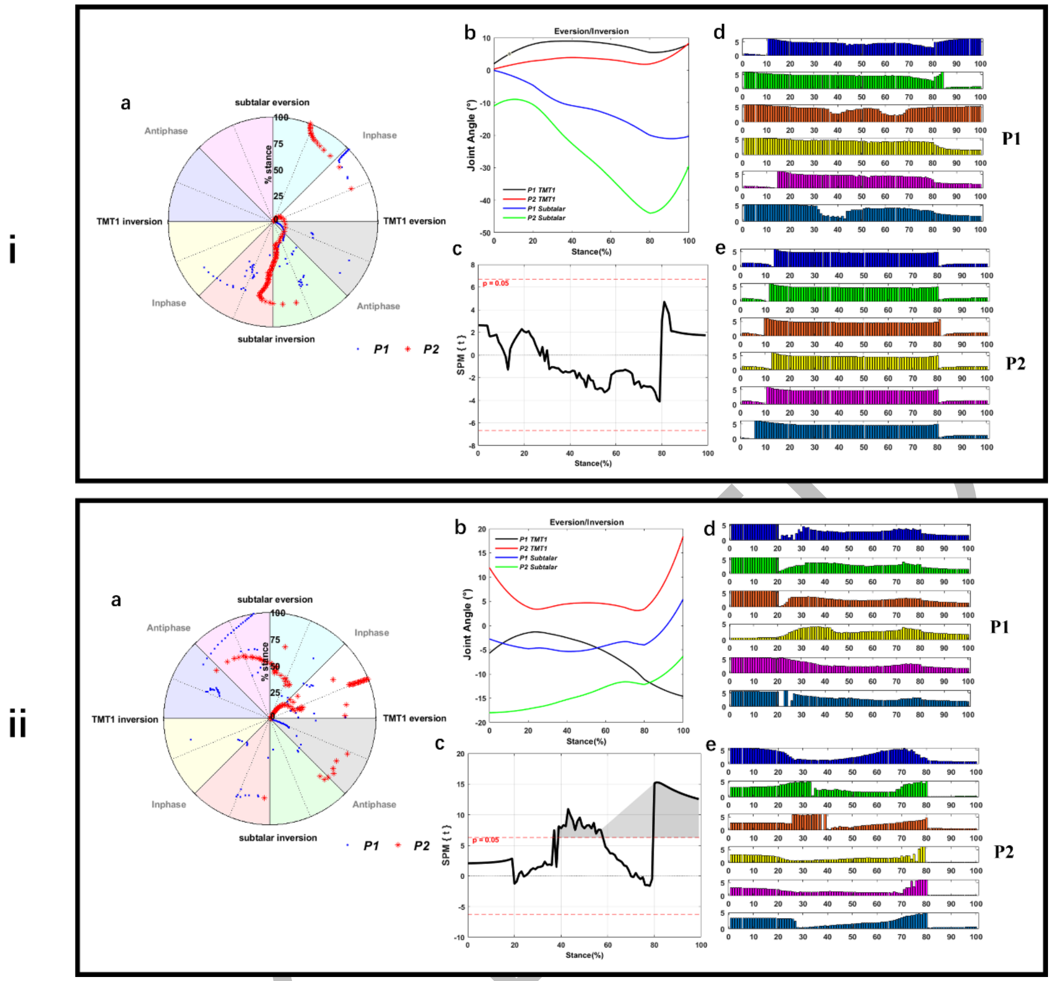

Figure 5. Mapping for subtalar-TMT1 coordination pattern (a) of injured lower limb between acute ankle sprain phase (P1) and 1-month recovery phase (P2); Comparison of subtalar and TMT1 joint angles with T0 (ib), T135 (iib); SPM1d analysis (c) of subtalar and TMT1 joint in gait; Individuals trials of hip-knee coordination in the frontal plane, respectively for six participants during stance phase of walking (d, e).

Figure 5 presented coupling angle of subtalar-TMT1 in the frontal plane. ankle-TMT1 coordination pattern was dominantly subtalar joint (proximal dominancy) during the T0 walking stance, especially P2 (Figure 5_i_a). Angles did not have great difference with subtalar and TMT1 joint (Figure 5_i_b, c). Six individual trails were different between P1 and P2(Figure 5_i_d,e). During T135 walking, P1 coupling angle was anti-phase with TMT1 joint (distal dominancy) in the early phase. P2 coupling angle was subtalar joint (proximal dominancy) in the middle phase. For late phase, P1 was anti-phase with subtalar joint (proximal dominancy) while P2 coordination pattern was in-phase with TMT1 joint (distal dominancy) (Figure 5_ii_a). Kinematic joint angles showed significant difference from 39% to the end of stance (Figure 5_ii_b,c). P1 individual six trails were similar apart from the forth and P2 individual late three trails were similar (Figure 5_ii_d,e). Figure S12 and Figure S13 placed the remaining two turning and uninjured lower limb with subtalar-TMT1.

Frontal Subtalar-TMT5 Coordination Pattern

The coupling angle mapping of subtalar-TMT5 was displayed in Figure6. P1 and P2 coordination pattern were mainly in-phase with subtalar joint (proximal dominancy) in the early and middle phase of straight walking. P1 coupling angle was in-phase with TMT5 joint (distal dominancy) in the late phase, but P2 coupling angle was in-phase with subtalar joint (proximal dominancy) (Figure6_i_a). Subtalar and TMT5 joint angles in straight walking had no remarkable difference (Figure6_i_b, c).

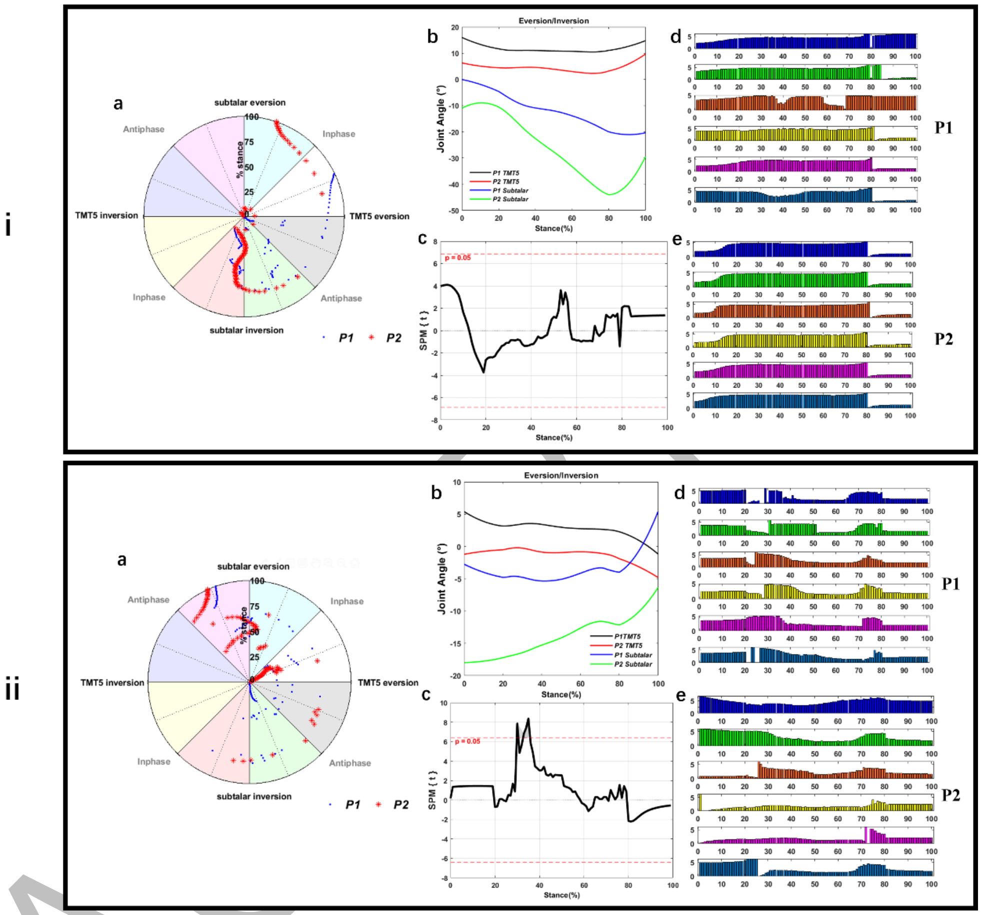

Figure 6. Mapping for subtalar-TMT5 coordination pattern (a) of injured lower limb between acute ankle sprain phase (P1) and 1-month recovery phase (P2); Comparison of subtalar and TMT5 joint angles with T0 (ib), T135 (iib); SPM1d analysis (c) of subtalar and TMT5 joint in gait; Individuals trials of hip-knee coordination in the frontal plane, respectively for six participants during stance phase of walking (d, e).

Except the first and third trails of P1, the other trails had similar trends (Figure6_i_d,e). According to Figure6_ii_a of T135 walking, P1 coupling angle was anti-phase with subtalar joint (proximal dominancy), but P2 was in-phase with TMT5 joint (distal dominancy) in the early phase. They were mostly anti-phase with subtalar joint (proximal dominancy) in the middle and late phase. From 30% to 35%, subtalar and TMT5 joint angles revealed obvious difference (Figure6_ii_b, c).P1and P2 individual trails were similar apart from early stance (Figure6_ii_d,e). T45 and T 90 and uninjured coupling angle mapping of subtalar-TMT5 were in Figure S14 and Figure S15.

Discussion

This pilot study evaluated segmental coordination of lower limb via comparing the gait kinematics of six participants with acute ankle sprain and over a 1-month return-to-play recovery period. P1 and P2 from this study showed that greater hip-knee, knee-ankle, ankle-MPT coordination variability in the sagittal plane and subtalar-TMT1, subtalar-TMT5 coordination variability in the frontal plane. Comparing with P2, P1 of walking in the four directions walking exhibited greater hip joint (proximal dominancy) in the late phase. P2 demonstrated greater ankle dorsiflexion (distal dominancy) in the middle and late phase than P1. Although there is no remarkable difference in inter-joint coordination of ankle-MTP, the coordination pattern was mainly MTP joint (distal dominancy) dominated in P2 and ankle joint (proximal dominancy) dominated in P1. In the frontal plane, ankle-TMT1 and ankle-TMT5 coupling angles displayed similar trend which was subtalar joint (proximal dominancy) during straight walking. P1 and P2 ankle-TMT1 and ankle-TMT5 coordination pattern matched worse with increasing turning angles, especially during T135 walking but fitted best in T45 walking, such as individual trails.

There were differences in correlation pattern of hip, knee and ankle joint between P1 and P2. Comparing with P2, P1 showed more hip joint (proximal dominancy) in Hip-Knee coupling angles. Moreover, P2 displayed more ankle dorsiflexion (distal dominancy) in Knee-Ankle joint coordination pattern. The result was reasonable given that one month after the acute ankle sprain improved the control and movement capacity of the proximal joint. This result was consistent with previous reports suggesting that the proximal joint played a critical role in maintaining balance during walking [6]. The inter-segmental coordination was important not only to control the lower limbs but also to maintain dynamic balance during walking [20]. Maintaining balance was the main function of supporting limbs during walking. This association suggested that higher inter-joint coordination variability could lead to poor balance or posture control [7]. Hence, in order to maintain balance and correct walking posture, it was necessary to practice and improve the inter-joint coordination of lower limb, especially the ankle joint training.

Ankle-MTP coordination exhibited no obvious difference with turning angles of walking, which indicated that the ankle and MTP joint were equally essential during stance. Whereas the dominant ankle joint of P1 suggested that there was an acute injury with individuals, it was inconvenient to use facet joint, such as MTP, while these individuals over 1-month period tended to use MTP joint as dominant joint. Compared with healthy older adults, Chiu et al. [7] found that only those who fall had greater ankle movement variability than those who did not fall, which was suggested that the variability of inter-segmental coordination in fallers was greater than that in healthy older adults. By testing the lower limb foot kinematics of 13 healthy people, Arnold et.al [2] found an increased frequency of proximal coordination between the ankle and tarsometatarsal joints, but it was only proposed that this difference could be due to the foot model since less metatarsal movement might facilitate proximal coordination pattern. However, this study was implied that individuals who were physically active were better able to use inter-joint coordination patterns, for example, individuals indicated MTP joint dorsiflexion to push off the ground in the late phase.

As the turning angle increasing, the Ankle-TMT1 and Ankle-TMT5 coupling angles of P1 and P2 became more and more separate until the T135 reached its maximum dispersion. This may indicate that turning affected inter-joint coordination patterns. Although turning in daily life was a typical movement, completing a directional turn while maintaining balance could be challenging, which was due to the fact that turning required greater coefficient of friction than walking in a straight line [12]. The study of 20 healthy men with a maximum speed of different turning (45°, 90° and 135°) found that sharper cutting angles increased the risk of chronic ankle injury [35]. Changing support points and greater ground reaction force (GRF) compared to walking in a straight line may increase the risk of falling while turning different angle directions [24, 36]. One previous study explored the gait of female elderly people, and proposed that without considering the turning angle, changing the walking direction was one of the biggest challenges to the balance ability of elderly people [28]. Therefore, challenge of greater turning angles may be sensitive to affect the foot coordination patterns, while also increasing the risk of falling or slipping [37]. Nonetheless, T45 in both P1 and P2 fitted well, which may indicate that T45 was a more suitable direction for humans to walk normally than other turning directions.

There are several limitations should be considered in this research. Firstly, only six female participants were recruited in this pilot study, while more individuals from other groups such as male and other age groups may provide comprehensive knowledge to understand the strategy of return-to-sport. Secondly, the current study only illustrated the inter-segmental coordination pattern with one primary plane of injured lower limb, understanding the coordination in other planes and healthy limbs may provide extra information for return-to-sport recovery. Thirdly, walking speed was self-selected by individuals. Although gait velocity would affect the inter-joint coordination variability [6], participants in this study were young adults with acute ankle sprain, and the self-selected speed was aimed to minimize the interference with natural gait performance. Future study shall consider the development of a more comprehensive experiment protocol with well-controlled gait conditions.

Conclusion

This study investigated the lower limb segmental coordination between acute ankle sprain and 1-month return-to-sport recovery period. The findings indicated that the increased lower limb coordination pattern could improve the turning gait stability. The increased turning degrees not only affected the inter-joint coupling angles but also increased the falling risk and gait instability. A notable point was to explore a new technique which was vector coding to analyze the lower limb kinematics from ankle sprain injury. The findings may reveal the inter-joint coordination variability and interaction and as a basis to distinguish the injured and healthy limb. Further, the findings in this study may be used to develop injury rehabilitation and return-to-sport programs for acute ankle sprain.

Conflict of interest

There is no commercial connection that would create a conflict of interest with the submitted article.

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Reference

[1] Aiken, A. B., Pelland, L., Brison, R., Pickett, W., & Brouwer, B. Short-term natural recovery of ankle sprains following discharge from emergency departments. Journal of Orthopaedic and Sports Physical Therapy, 2008, 38(9), 566–571. https://doi.org/10.2519/jospt.2008.2811

[2] Arnold, J. B., Caravaggi, P., Fraysse, F., Thewlis, D., & Leardini, A. Movement coordination patterns between the foot joints during walking. Journal of Foot and Ankle Research, 2017,10(1), 1–7. https://doi.org/10.1186/s13047-017-0228-z

[3] Bigoni, M., Turati, M., Gandolla, M., Augusti, C. A., Pedrocchi, A., La Torre, A., Piatti, M., & Gaddi, D. Balance in young male soccer players: dominant versus non-dominant leg. Sport Sciences for Health, 2017,13(2), 253–258. https://doi.org/10.1007/s11332-016-0319-4

[4] Caulfield, B. M., & Garrett, M. Functional instability of the ankle: Differences in patterns of ankle and knee movement prior to and post landing in a single leg jump. International Journal of Sports Medicine, 2002,23, 64–68. https://doi.org/10.1055/s-2002-19272

[5] Chang, R., Van Emmerik, R., & Hamill, J. Quantifying rearfoot-forefoot coordination in human walking. Journal of Biomechanics, 2008, 41(14), 3101–3105.

[6] Chiu, S. L., & Chou, L. S. Effect of walking speed on inter-joint coordination differs between young and elderly adults. Journal of Biomechanics, 2012, 45(2), 275–280.

[7] Chiu, S. L., & Chou, L. S. Variability in inter-joint coordination during walking of elderly adults and its association with clinical balance measures. Clinical Biomechanics, 2013, 28(4), 454–458. https://doi.org/10.1016/j.clinbiomech.2013.03.001

[8] Chockalingam, N., Needham, R., Healy, A., & Naemi, R. Coordination pattern between the forefoot and rearfoot during walking on an inclined surface. Footwear Science, 2017,9(8), S120–S122. https://doi.org/10.1080/19424280.2017.1314372

[9] Crosbie, J., Green, T., & Refshauge, K. Effects of reduced ankle dorsiflexion following lateral ligament sprain on temporal and spatial gait parameters. Gait and Posture, 1999, 9(3), 167–172. https://doi.org/10.1016/S0966-6362(99)00010-7

[10] Doherty, C., Delahunt, E., Caulfield, B., Hertel, J., Ryan, J., & Bleakley, C. The Incidence and Prevalence of Ankle Sprain Injury: A Systematic Review and Meta-Analysis of Prospective Epidemiological Studies. Sports Medicine, 2014, 44(1), 123–140.

[11] During, I., Exercise, R., Lucas, R. D. De, Beneke, R., Guilherme, L., Guglielmo, A., & Effort, P. Hop Stabilization Training Improves Neuromuscular Control in Collegiate Basketball Players with Chronic Ankle Instability: A Randomized Controlled Trial. Motor Control. Journal of Sport Rehabilitation, 2019, 28(6), 576–583. https://doi.org/10.1123/jsr.2018-0103

[12] Fino, P., & Lockhart, T. E. Required coefficient of friction during turning at self-selected slow, normal, and fast walking speeds. Journal of Biomechanics, 2014, 47(6), 1395–1400.

https://doi.org/10.1016/j.jbiomech.2014.01.032

[13] Fong, D. T., Chan, Y.-Y., Mok, K.-M., Yung, P. S., & Chan, K.-M. Understanding acute ankle ligamentous sprain injury in sports. BMC Sports Science, Medicine and Rehabilitation, 2009,1(1), 1–14. https://doi.org/10.1186/1758-2555-1-14

[14] Gill, C., & Batschelet, E. Circular Statistics in Biology. In Journal of the Royal Statistical Society. 1983, 146(1). https://doi.org/10.2307/2981498

[15] Hamill, J., Haddad, J. M., & McDermott, W. J.. Issues in Quantifying Variability from a Dynamical Systems Perspective. Journal of Applied Biomechanics, 2000, 16(4), 407–418. https://doi.org/10.1123/jab.16.4.407

[16] Heiderscheit, B. C., Hamill, J., & van Emmerik, R. E. A. Variability of Stride Characteristics and Joint Coordination among Individuals with Unilateral Patellofemoral Pain. Journal of Applied Biomechanics, 2002, 18(2), 110–121. https://doi.org/10.1123/jab.18.2.110

[17] Hølmer, P., Søndergaard, L., Konradsen, L., Nielsen, P. T., & Jørgensen, L. N. Epidemiology of Sprains in the Lateral Ankle and Foot. Foot & Ankle International, 1994, 15(2), 72–74. https://doi.org/10.1177/107110079401500204

[18] Houston, M. N., Van Lunen, B. L., & Hoch, M. C. Health-related quality of life in individuals with chronic ankle instability. Journal of Athletic Training, 2014, 49(6), 758–763. https://doi.org/10.4085/1062-6050-49.3.54

[19] Kowalczyk, M., & Truszczyńska-Baszak, A. The impact of fatigue on static balance in people with chronic ankle instability. Acta of Bioengineering and Biomechanics, 2023, 25(1), 151–160. https://doi.org/10.37190/ABB-02214-2023-02

[20] Lacquaniti, F., Lucia, F. S., Borghese, N. A., & Bianchi, L. Posture and movement : Coordination and control. Arch Itail Biol, 1997, 135(4), 353–367.

[21] Lee, C., & Moudon, A. V. Physical Activity and Environment Research in the Health Field: Implications for Urban and Transportation Planning Practice and Research. Journal of Planning Literature, 2004, 19(2), 147–181. https://doi.org/10.1177/0885412204267680

[22] Liu, S. H., & Nguyen, T. M. Ankle sprains and other soft tissue injuries. In Current Opinion in Rheumatology 1999,11, (2) 132–137. https://doi.org/10.1097/00002281-199903000-00009

[23] Maharaj, J. N., Rainbow, M. J., Cresswell, A. G., Kessler, S., Konow, N., Gehring, D., & Lichtwark, G. A. Modelling the complexity of the foot and ankle during human locomotion: the development and validation of a multi-segment foot model using biplanar videoradiography. Computer Methods in Biomechanics and Biomedical Engineering, 2022, 25(5), 554–565. https://doi.org/10.1080/10255842.2021.1968844

[24] Nolasco, L. A., Silverman, A. K., & Gates, D. H. Whole-body and segment angular momentum during 90-degree turns. Gait & Posture, 2019, 70(2), 12–19.

[25] Pohl, M. B., Messenger, N., & Buckley, J. G. Forefoot, rearfoot and shank coupling: Effect of variations in speed and mode of gait. Gait and Posture, 2007, 25(2), 295–302. https://doi.org/10.1016/j.gaitpost.2006.04.012

[26] Punt, I. M., Ziltener, J. L., Laidet, M., Armand, S., & Allet, L. Gait and physical impairments in patients with acute ankle sprains who did not receive physical therapy. PM and R, 2015, 7(1), 34–41. https://doi.org/10.1016/j.pmrj.2014.06.014

[27] Repository, I. Evidence review for the 2016 International Ankle Consortium consensus statement on the prevalence, impact and long-term consequences of lateral ankle sprains. Loughborough University, 2016,1496–1505.

[28] Shin, S. S., & Yoo, W. G. Effects of gait velocity and center of mass acceleration during turning gait in old-old elderly women. Journal of Physical Therapy Science, 2015, 27(6), 1779–1780. https://doi.org/10.1589/jpts.27.1779.

[29] Smith, R. W., & Reischl, S. F. Treatment of ankle sprains in young athletes. The American Journal of Sports Medicine, 1986, 14(6), 465–471. https://doi.org/10.1177/036354658601400606

[30] Sparrow, W. A., Donovan, E., van Emmerik, R., & Barry, E. B. Using Relative Motion Plots to Measure Changes in Intra-Limb and Inter-Limb Coordination. Journal of Motor Behavior, 1987, 19(1), 115–129. https://doi.org/10.1080/00222895.1987.10735403

[31] Takabayashi, T., Edama, M., Nakamura, E., Yokoyama, E., Kanaya, C., & Kubo, M. Coordination among the rearfoot, midfoot, and forefoot during walking. Journal of Foot and Ankle Research, 2017, 10(1), 1–9. https://doi.org/10.1186/s13047-017-0224-3

[32] Turati, M., Boerci, L., Piatti, M., Zanchi, N., Zatti, G., Accadbled, F., & Bigoni, M. What's new about etiopathogenesis of musculoskeletal injuries in adolescent athletes? Minerva Pediatrics. 2020, https://doi.org/10.23736/S0026-4946.20.05944-7

[33] Yu, P., Cen, X., Mei, Q., Wang, A., Gu, Y., & Fernandez, J. Differences in intra-foot movement strategies during locomotive tasks among chronic ankle instability, copers and healthy individuals. Journal of Biomechanics, 2024, 162(818), 111865.

[34] Yu, P., Cen, X., Xiang, L., Mei, Q., Wang, A., Gu, Y., & Fernandez, J. Regional plantar forces and surface geometry variations of a chronic ankle instability population described by statistical shape modelling. Gait & Posture, 2023, 106(818), 11–17.

[35] Zhou, W., Qi, Y., Liu, M., Hsiao, C., & Wang, L. Effect of foot strike patterns and cutting angles on knee kinematics and kinetics during side-cutting maneuvers. Acta of Bioengineering and Biomechanics, 2023,25(1), 27–34. https://doi.org/10.37190/ABB-02192-2023-022

[36] Yamane, T., Yamasaki, Y., Nakashima, W. and Morita, M. Tri-Axial Accelerometer-Based Recognition of Daily Activities Causing Shortness of Breath in COPD Patients. Physical Activity and Health, 2023, 7(1), 64–75. https://doi.org/10.5334/paah.224

[37] Pérez-Cruzado, D., González-Sánchez, M., Cuesta-Vargas, A.I. Differences in kinematic variables in single leg stance test between young and elderly people. International Journal of Biomedical Engineering and Technology, 2023, 42(2), 167–183. https:// 10.1504/IJBET.2017.085442