Gait Kinematics of Patients with Lateral Collateral Ligament Injuries of Ankle

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Research

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Gait Kinematics of Patients with Lateral Collateral Ligament Injuries of Ankle

（Research article prepared for JTM）

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ABSTRACT

Background：Lateral collateral ligament (LCL) injuries of ankle are a common problem in sports medicine. The purpose of this study is to evaluate the walking kinematics in patients with LCL injuries of ankle for examining how ankle ligament injuries affect foot and ankle motion. The results will serve in precision assessment and computer-aided diagnosis.

Methods：Kinematics of walking were assessed by the Heidelberg Foot Measurement Model (HFMM) in 6 adults (3 patients, 3 control subjects). We hypothesized that patients with ligament injury will: present a shorter stance phase, but longer swing phase; be observed with an increasing number of shank and foot adjustments during the stance phase; reduce velocity of foot during the early swing phase with an increasing variation. Velocity profiles and micro-adjustment of knee, ankle, and foot were calculated during different gait phases and compared between two different subject groups by independent-sample t-test with 95% confidence intervals and standard error of measurements.

Results：In the gait cycle, 1^{st} rocker phase was 2.09% shorter ($p < 0.001$) and 2^{nd} rocker phase was 1.54% longer ($p = 0.009$) in patients than in controls. Compared to control subjects, the patients showed 89.1 mm shorter stride length ($p<0.001$), 0.10s slower stride ($p<0.001$) and 1.57 more complex micro-adjustments in 2^{nd} rocker phase than in other rocker/swing phases during natural walking ($p=0.017$). The mean velocity of knee (6.05 mm/10^{-2}s vs. 4.74 mm/10^{-2}s), ankle (0.85 mm/10^{-2}s vs. 0.52 mm/10^{-2}s), midfoot (0.79 mm/10^{-2}s vs. 0.48 mm/10^{-2}s) and forefoot (1.72 mm/10^{-2}s vs. 0.97 mm/10^{-2}s) in 2^{nd} rocker was significantly higher in patients ($p<0.001$).

Conclusion: Our findings revealed the human motion compensatory mechanism. Patients with ligament injuries need more musculoskeletal adjustments to keeping body balance than control subjects. Precise descriptions of the kinematics are crucial for clinical assessment before and after surgical management. These results will also provide a foundation for computer-aided diagnosis in the future.

Key Terms: ankle ligaments, gait analysis, Heidelberg Foot Measurement Model, foot and ankle kinematics, phase/rocker, physical therapy/rehabilitation.

BACKGROUND

Foot and ankle injuries are a common problem worldwide (1). The incidence rate of LCL injuries of ankle was reported to be one in every 10,000 people per day in the world, ranking the highest among trauma cases in the emergency (2). Each year in China, more than one million people suffer from ligament injuries surrounding the foot and ankle, costing over one billion for treatment and rehabilitation (3).

In current practice, physicians make diagnoses of ligament injuries base on physical and medical examinations. Clinical evidences allow physicians to describe the location of injury and give treatment advice to patients. For some patients, such as those frequently reoccurrence cases, surgical management (including casting, splinting, ligament surgery) are necessary (4).

When ligaments surrounding patients' foot and ankle get injured, patients' mobilization will be affected. Current clinical diagnosis and management do not routinely include gait analysis (5). Without gait analysis limits our understanding of patients' injuries and impacts on locomotion. Many scientists argued that gait analysis should in included necessary for patients with foot and ankle ligament injuries, especially on those serious and frequent cases (6).

To examine foot and ankle motion, we need to place markers on multiple segments of the lower extremity. In recent years, several tracking models have been developed to measure the foot and ankle motions precisely. For example, the Oxford Foot Model (including the shank, hindfoot, forefoot, and hallux) has been used routinely in clinical practice to assess foot deformity and gait dysfunction, such as idiopathic clubfoot, foot arthritis, cerebral palsy, hemiplegia [(7-10)]. The Milwaukee Foot Model, a four-segment model (tibia, hindfoot, forefoot, and hallux), has been applied to identify atypical segmental foot motion during ambulation and measure the intervention effectiveness after operations for the hallux valgus, hallux rigidus, posterior tibial tendon dysfunction, systemic rheumatoid arthritis and forefoot deformity [(11-14)].

However, the Oxford Foot Model and Milwaukee Foot Model do not include the midfoot segment for gait analysis. To fill this gap, the Istituti Ortopedici Rizzoli Foot model and three-dimensional(3D) foot model were developed to cover five-segment on the leg (shank, calcaneus, midfoot, metatarsals, and hallux) [(15, 16)].The Kinfoot model is a nine-segment model to cover the shank, hindfoot, two midfoot segments, two forefoot segments, two toe segments and a hallux (17). However, these three models only focus on the loaded foot in the stance phase, neglecting the unloaded foot in the swing phase.

The Heidelberg Foot Measurement Model (HFMM), covering segments of the shank, the hindfoot, the midfoot and the forefoot (both medial and lateral segments of the forefoot and hallux), is developed to analyze foot and ankle kinematics in the entire gait cycle [(18)]. HFMM model is recommended to patients with LCL injuries of ankle. It can provide velocity and angular movement description which helps us to characterize the multi-segmental motion of the foot and ankle in cases of LCL injuries of ankle.

The main objective of this study is to search for the specific characteristics of patients suffering from LCL injuries of ankle during the entire gait cycle. To achieve the goal, we recruit patients with LCL injuries of ankle and pair them up with healthy adults; tracking the leg movement in the gait analysis lab using HFMM; calculating kinematic features during stance and swing phases. We hypothesized that patients with ligament injury will: 1) present a shorter stance phase, but longer swing phase for shortening weight-bearing in the affected foot than the control subjects; 2) be observed with an increasing number of shank and foot adjustments during the stance phase; and 3) reduce velocity of foot during the early swing phase with an increasing variation due to unstable ankle position.

METHODS

Participants

This study was carried out in the Peking University Third Hospital in collaboration with the University of Science and Technology Beijing. The protocol was approved by the Ethics Review Committee at the hospital and each participant provided written consent before they enrolled in the study.

The inclusion criterion of the injury group are as follows: 1) diagnosed with LCL injuries of ankle without bone fracture (by X-ray inspection); 2) multiple lateral ankle sprains requiring surgical treatment; 3) 3-6 months after recent sprain as we were examining the long-term impact of ligament injuries on the mobilization; 4) age range from 18 to 40.

The exclusion criterion of the injury group are as follows: 1) acute and subacute ligament injury within 1-3 months; 2) combining with ankle osteoarthritis or cartilage injury; 3) ankle inversion/eversion over 5 degrees; 4) compared with the normal side, the activity range of the injured ankle reduces over 10 degrees; 5) combining with knee/hip osteoarthritis, ligaments injury, cartilage injury et al.; 6) with neurologic abnormality; 7) with other serious medical diseases that reduced mobile ability.

Healthy adults with paired age and gender were recruited from the student and staff of the hospital and university to serve as control subjects.

Data acquisition

To capture motions of foot and ankle of subjects, we placed a total of 17 infra-red markers (13 of 9 mm, 4 of 14 mm reflective markers) on the key bony landmarks of each leg (Figure 1a, Table 1) following the Heidelberg Foot Measurement Model [(18)]. Three-dimensional (3D) motions of these markers were captured by the Vicon MX Motion Capture System (developed by Lucent Technologies Inc.) that consisted of eight MX Cameras. The Vicon System used infrared strobes to illuminate reflective markers and captured their 3D position data at 100 Hz. When fed to the special software, we extracted foot and ankle kinematics of four leg segments (shank, hindfoot, midfoot, and forefoot) in the global coordinate system of the gait analysis lab.

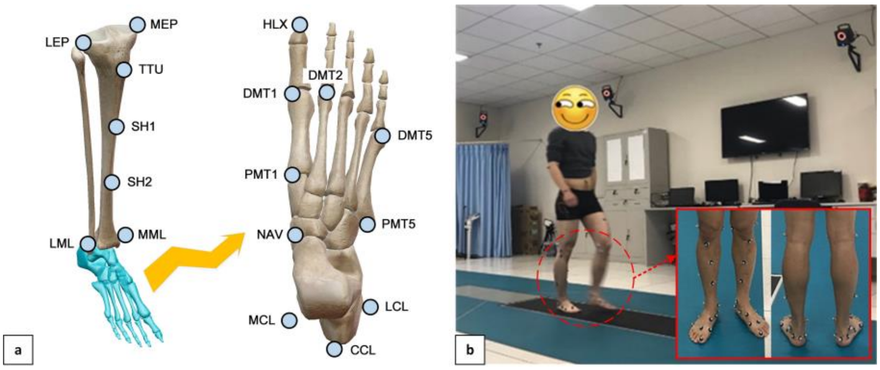

Figure 1. (a) Marker placement based on HFMM. LEP/MEP: lateral/medial epicondyle; TTU: tibia tuberosity; SH1/2: two points on the medial side of the shin; LML/MML: lateral/medial malleolus; LCL/CCL/MCL: lateral/dorsal/ medial calcaneus; NAV: navicular; PMT1/PMT5: proximal end of 1st5th metatarsal; DMT1/2/5: distal end of 1st/2nd/5th metatarsal; HLX: hallux. (b) Tracking movement of subjects by Vicon MX Motion Capture System.

Table 1. Markers and locations.

Segment	Marker	Location
Tibia & Fibula (Shank)	LEP/MEP	Lateral and medial of the knee, the line through the markers determine the largest distance of the knee flexion axis.
	TTU	Most prominent part of tibia tuberosity.
	SH1/SH2	Two points on the medial side of the shin dividing the tibia into three equal parts.
	LML/MML	Lateral and medial malleolus, the line through the makers determine the largest distance of malleolus.
Tarsals (Hindfoot)	LCL/CCL/MCL	Most Prominent part of lateral/dorsal/ medial calcaneus.
	NAV	Navicular, the marker axis is about 45°to the floor from the frontal view.
Metatarsals (Midfoot)	DMT1/2/5	Distal end of 1st/2nd/5th metatarsal.
	PMT1/5	Proximal end of 1st/5th metatarsal.
Phalanges (Forefoot)	HLX	Midpoint of the distal phalanges of hallux.

Each subject was required to walking in barefoot along a 10-meter flat path at the subject's comfort speed (Figure 1b). A minimum of five walking trials was used for analysis. The raw position data for each marker exported as .csv files from Vicon MX Motion Capture System for future analysis.

Data analysis

Kinematics of motion data were calculated using a set program written in MATLAB R2018a.

Pre-processing

The raw motion data were filtered by a low-pass zero phase shift first-order *Butterworth* filter with no more than 1dB of ripple in passband from 0 to 0.01Hz, and at least 3dB of attenuation in the stopband above 20Hz.

Gait cycle, phases, and rockers definition

An intact gait cycle includes *stance phase* (from heel-strike to toe-off) and *swing phase* (from toe-off to heel-strike again). A stance phase is divided into three *rocker phases*: the 1st rocker phase is from heel-strike to foot-flat; the 2nd rocker phase is from foot flat to heel-off; the 3rd rocker phase is from heel-off to toe-off. The gait cycles, phases, and rockers are split according to the following method shown in Figure 2.

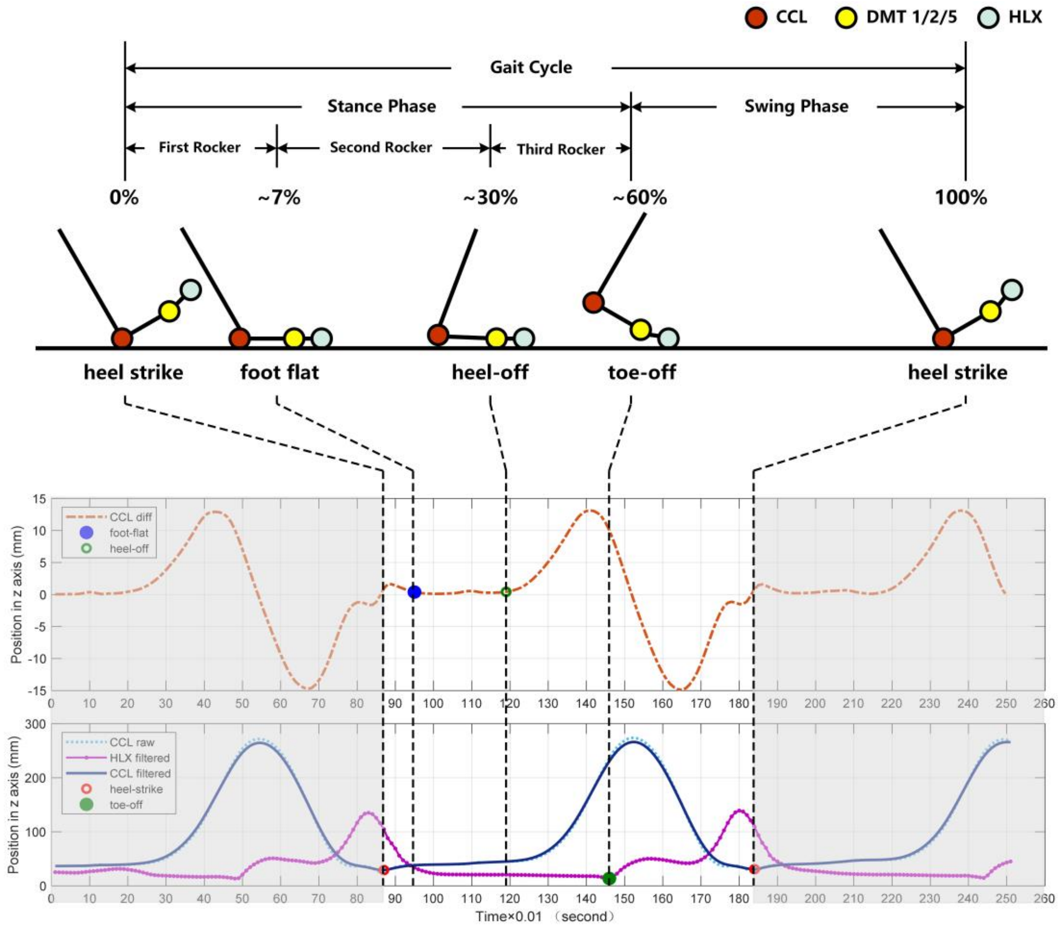

Figure 2. Gait cycles, phases and rockers splitting.

The beginning of gait cycles is defined by the marker CCL in the dorsal calcaneus. When the position of CCL at Z-axis reaches a minimal value (Figure 2: the circles in CCL filtered line), this moment is defined to the beginning of a new gait cycle.

The new gait cycle starts with a stance phase, where the toe lowers gradually to the floor gripping forcefully until toe-off (Figure 2: the point in the HLX filtered line). We use the Z-axis minimum value of the HLX marker in gait cycle to divide stance phase and swing phase in a gait cycle.

The separation of three rocker phases is defined by the CCL and DMT markers at their Z-axis position. Once the stance phase begins, the position of CCL Z-axis reaches a minimal value at heel-strike then the plantarflexion increases until the DMT marker reaching to the floor. When the interframe difference of CCL Z-axis position is below 0.5 mm, the 2nd rocker foot-flat starts (Figure 2: the point in the CCL diff line). During the 2nd rocker phase, the foot lays flat on the floor and the CCL position at Z-axis maintains stable excepting for a few minor jitters caused by elastic deformation of skin in dorsiflexion. In this phase, interframe difference fluctuates is within a small threshold or monotone increasing less than 1mm. When the 3rd rocker phase begins (the heel off), the interframe difference increases rapidly (interframe diff ≥ 1mm, Figure 2: the circle in the CCL diff line). The CCL position at Z-axis increases rapidly in the 3rd rocker phase until the toe-off.

Velocity

Five markers were chosen for calculating velocity profiles, including the TTU (knee), LML (ankle), CCL (hindfoot), DMT2 (midfoot) and HLX (forefoot). These markers were largely independent of each other and were considered clinically relevant as they can reveal pathologic features of the gait after LCL injuries of ankle. The velocity calculation is as follows:

$$v = \frac{\sqrt[2]{\Delta M_x^2 + \Delta M_y^2 + \Delta M_z^2}}{\Delta t}$$

Here, v is velocity; ΔM_x, ΔM_y, ΔM_z are the position differences between two sampling points in X-axis, Y-axis, Z-axis; Δt is the time difference between two samplings.

On each marker, the maximum velocity (V_{max}), the minimum velocity (V_{min}) and the time to maximum velocity (TV_{max}) and minimum velocity (TV_{min}) were reported. To make data comparable between patients and control subjects, we normalized each gait cycle to 100 sampling points.

Statistics

Gait and kinematical variables, including stride length, stride duration, normalized phase durations, and velocities, were compared between ligament injury patients and the control subjects. All statistics were calculated through the use of SPSS Statistics for Windows, Version 25.0 (IBM Corp, Chicago, USA). Mean and Standard Error (SE) are reported for significant effects, with an a priori level of 0.05. The statistical graphs were based on MATLAB R2018a.

RESULTS

This study reports gait data captured from three patients diagnosed with LCL injuries of ankle prior to surgery (all male, mean age of 34 years, range: 32-37 years). All the patients were treated and recommended by one surgeon specialized in sport medicine. Three control subjects (all male, mean age 26 years, range: 25-28 years) were recruited. Demographics are reported in Table 2.

Table 2. Demographics.

	Patient	**Control**
number of participants	3	3
age	34 years old (range: 32 - 37)	26 years old (range: 25 - 28)
sex	male	male
BMI (Mean ± SD)	26.39 ± 4.64	19.07 ± 3.46
affected side	2 right (P1, P2) / 1 left (P3)	--

Gait analysis

On average, ligament injury patients walked slower with smaller strides compared to control subjects. Specifically, stride length was reduced from 1419.8 mm to 1330.7 mm ($p < 0.001$), and stride duration was increased from 0.98 to 1.08 s/stride ($p < 0.001$, Table 3).

Phases difference

Comparison of the gait phases between the LCL injuries of ankle patients and control subjects showed significantly shorter percent in the 1st rocker phase (4.67% vs.

6.76%, $p < 0.001$) and longer in the 2nd rocker phase (25.80% ± 0.39 vs. 24.26% ± 0.38, $p = 0.009$; Table 3). No significant differences were found in the 3rd rocker phase ($p = 0.656$), nor in total stance or swing phases ($p = 0.849$).

Table 3. Temporal measure.

Parameter	**Patient** (n = 30, gait cycle #)	**Control** (n = 50, gait cycle #)	**p-value**
	Mean ± SE	***Mean ± SE***	
percent 1st rocker (%)	4.67 ± 0.15	6.76 ± 0.16	**< 0.001**
percent 2nd rocker (%)	25.80 ± 0.39	24.26 ± 0.38	**0.009**
percent 3rd rocker (%)	28.50 ± 0.88	28.12 ± 0.40	0.656
percent stance phase (%)	58.97 ± 0.88	59.14 ± 0.20	0.849
percent swing phase (%)	41.03 ± 0.88	40.86 ± 0.20	0.849
stride length (mm)	1330.7 ± 6.35	1419.8 ± 7.46	**< 0.001**
duration (s/stride)	1.08 ± 0.01	0.98 ± 0.01	**< 0.001**

Velocity measure

The leg velocity profiles are displayed in Figure 3. Please note that gait cycles were normalized to time. In control subjects, gait recorded from both legs was averaged and compared to gait recorded from the affected side of the leg of patients.

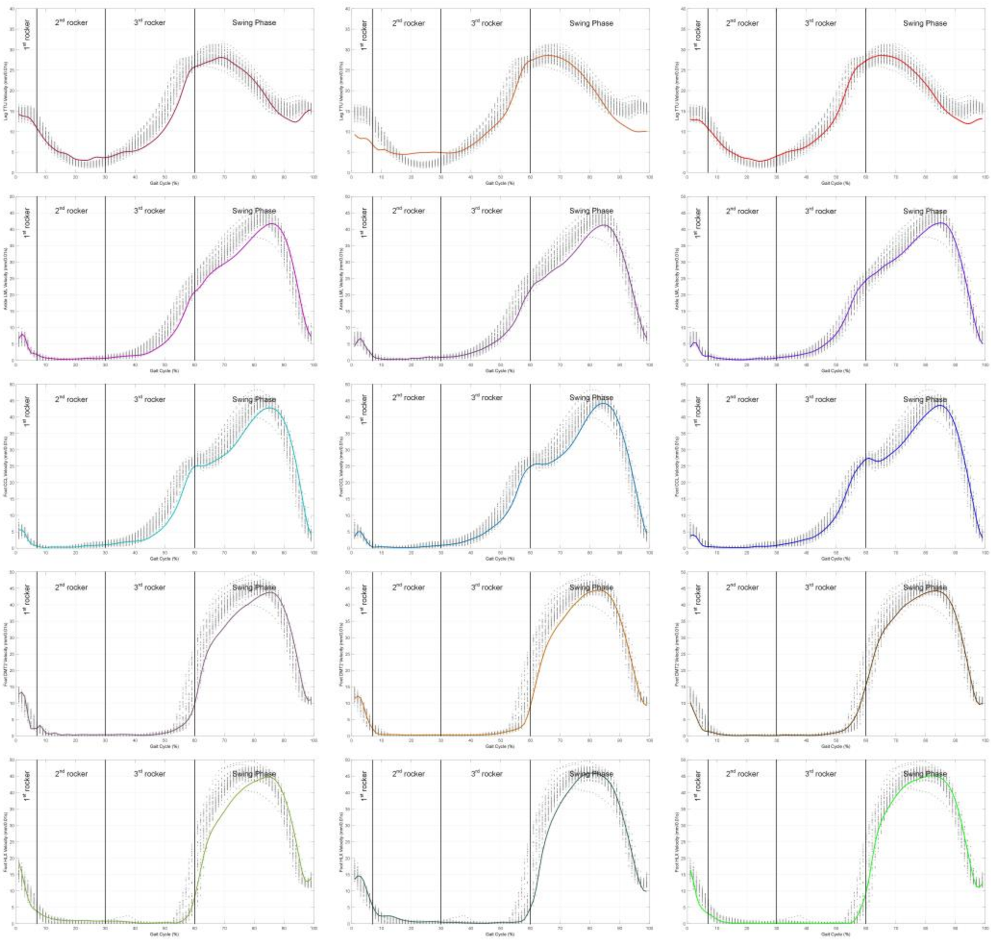

Figure 3. Velocity profiles of five anatomic landmarks (in row, marked by five sensors; TTU, LML, CCL, DMT2, HLX) over entire gait cycles of three patients (in column). Please noted that each gait cycle is normalized in time and the phases are separated by three long vertical lines. On each marker, the mean velocity profile (solid lines) over ten strides of patient are displayed on top of fifty velocity curves (grey dots) taken from three normal participants.

As shown in Table 4, V_{max} is significantly different in all five markers between patients and control subjects; basically, patients' maximum velocity is higher than the control subjects. The TV_{max} also display significant differences in all markers except for the TTU; specifically, patients reach peak velocity later than control subjects. The V_{min} displays a significant difference only for the TTU, LML, DMT2. In these markers, V_{min} is higher in patients than in control subjects. The TV_{min} only shows significance on the TTU marker, where control subjects reach to minimum velocity later than patients.

Table 4. Velocity measure in gait cycle.

Marker	Parameter in GC	Patient (n = 30, gait cycle #)	Control (n = 50, gait cycle #)	p-value
		Mean ± SE	***Mean ± SE***	
TTU	V_{max} (mm/10^{-2}s)	30.73 ± 0.43	27.95 ± 0.20	**< 0.001**
	TV_{max} (%)	66.57 ± 0.40	66.62 ± 0.39	0.929
	V_{min} (mm/10^{-2}s)	3.48 ± 0.21	1.77 ± 0.05	**< 0.001**
	TV_{min} (%)	22.07 ± 0.76	24.28 ± 0.23	**0.009**
LML	V_{max} (mm/10^{-2}s)	45.06 ± 0.57	42.35 ± 0.30	**< 0.001**
	TV_{max} (%)	85.33 ± 0.23	82.92 ± 0.24	**< 0.001**
	V_{min} (mm/10^{-2}s)	0.26 ± 0.02	0.12 ± 0.01	**< 0.001**
	TV_{min} (%)	16.50 ±0.70	16.74 ± 0.60	0.801
CCL	V_{max} (mm/10^{-2}s)	47.15 ± 0.74	43.59 ± 0.29	**< 0.001**
	TV_{max} (%)	84.80 ± 0.22	83.06 ± 0.19	**< 0.001**
	V_{min} (mm/10^{-2}s)	0.14 ± 0.01	0.12 ± 0.01	0.134
	TV_{min} (%)	13.83 ± 0.56	12.54 ± 0.47	0.087
DMT2	V_{max} (mm/10^{-2}s)	47.76 ± 0.68	44.41 ± 0.27	**< 0.001**
	TV_{max} (%)	83.77 ± 0.33	81.66 ± 0.21	**< 0.001**
	V_{min} (mm/10^{-2}s)	0.13 ± 0.01	0.09 ± 0.01	**0.002**
	TV_{min} (%)	29.50 ± 2.04	28.40 ± 1.27	0.650
HLX	V_{max} (mm/10^{-2}s)	49.03 ± 0.77	44.95 ± 0.26	**< 0.001**
	TV_{max} (%)	82.50 ± 0.43	79.44 ± 0.42	**< 0.001**
	V_{min} (mm/10^{-2}s)	0.07 ± 0.01	0.08 ± 0.00	0.600
	TV_{min} (%)	42.83 ± 1.86	39.78 ± 1.91	0.255

Note: V_{max}: maximum velocity, V_{min}: minimum velocity, TV_{max}: time to maximum velocity; TV_{min}: Time to minimum velocity

Foot adjustment

Visual inspection in Figure 3, we found that a larger deviation of velocity profiles of patients from the control subjects occurred during the 2nd rocker phase. This observation aligned with increasing difficulty in maintaining the stability of foot and ankle after injuries of surrounding ligaments. To quantify the efforts for stability adjustment, we measured the number of *velocity adjustments* during the three rockers and swing phase (Table 5).

Table 5. Number of subjects' velocity adjustment during three rockers and swing phase.

Parameter	Patient (n = 30, gait cycle #)	Control (n = 50, gait cycle #)	p-value
	Mean ± SE	***Mean ± SE***	
Adjustment num in 1st Rocker	0.87 ± 0.14	0.57 ± 0.10	**0.097**
Adjustment num in 2nd Rocker	4.87 ± 0.54	3.20 ± 0.38	**0.017**
Adjustment num in 3rd Rocker	2.00 ± 0.24	1.67 ± 0.17	0.273
Adjustment num in Swing Phase	1.80 ± 0.14	1.87 ± 0.10	0.696

Compared to control subjects, patients with ligament injuries made more adjustments in the stance but not the swing phase. However, the only significant difference occurred in the 2nd rocker phase (4.87 ± 0.54 vs. 3.20 ± 0.38, p = 0.017). In the 2nd rocker phase, the keen, the ankle, the calcaneus and the midfoot of patients have significant acceleration and deceleration. The patients' mean velocity of the keen, the ankle, the midfoot and the forefoot in the 2nd rocker phase is more rapid (Table 6).

Table 6. Velocity measure in 2nd rocker phase.

Marker	Parameter in 2nd Rocker	Patient (n = 30, gait cycle #)	Control (n = 50, gait cycle #)	p-value
		Mean ± SE	***Mean ± SE***	
TTU	minimal value num.	2.47 ± 0.23	1.16 ± 0.07	**<0.001**
	maximal value num.	1.87 ± 0.25	0.22 ± 0.06	**<0.001**
	velocity (mm/10^{-2}s)	6.05 ± 0.07	4.74 ± 0.08	**<0.001**
LML	minimal value num.	3.73 ± 0.19	3.16 ± 0.12	**0.007**
	maximal value num.	2.97 ± 0.17	2.34 ± 0.13	**0.004**
	velocity (mm/10^{-2}s)	0.85 ± 0.03	0.52 ± 0.02	**<0.001**
CCL	minimal value num.	3.37 ± 0.19	2.94 ± 0.17	0.106
	maximal value num.	2.67 ± 0.18	2.14 ± 0.16	**0.040**
	velocity (mm/10^{-2}s)	0.54 ± 0.02	0.57 ± 0.03	0.404
DMT2	minimal value num.	3.80 ± 0.34	3.02 ± 0.13	**0.041**
	maximal value num.	3.50 ± 0.35	2.36 ± 0.13	**0.005**
	velocity (mm/10^{-2}s)	0.79 ± 0.03	0.48 ± 0.01	**<0.001**
HLX	minimal value num.	2.10 ± 0.17	2.28 ± 0.12	0.372
	maximal value num.	1.67 ± 0.17	1.60 ± 0.12	0.740
	velocity (mm/10^{-2}s)	1.72 ± 0.10	0.97 ± 0.04	**<0.001**

Note: TTU: tibia tuberosity; LML: lateral malleolus; CCL: dorsal calcaneus; DMT2: distal 2nd metatarsal; HLX: hallux.

Different movement segments displayed different adjustment strategies in both the stance and swing phase (Table 7). In the 1st rocker phase, the knee (1.08), the ankle (1.00), and the calcaneus (1.00) displayed more adjustment than the midfoot (0.33) and the forefoot (0.17). In the 2nd rocker phase, the significantly large number of adjustments occurred in the midfoot (6.33), the ankle (4.83), the calcaneus (3.83) than the forefoot (3.00) and the knee (2.17). In the 3rd rocker phase, the significantly large number of adjustments occurred in the midfoot (3.50) and the forefoot (5.17) than the knee (0.17), the ankle (0.17), the calcaneus (0.17). In the swing phase, the significantly large number of adjustments occurred in the knee (2.50) and the calcaneus (2.50) than the midfoot (1.50), the forefoot (1.67), and the ankle (1.00).

Table 7. Number of segments' velocity adjustment during the three rockers and swing phase.

Parameter	TTU	LML	CCL	DMT2	HLX	*SE*	P value
	Mean	***Mean***	***Mean***	***Mean***	***Mean***		
Adjustment num in 1st Rocker	1.08	1.00	1.00	0.33	0.17	0.20	**0.003**
Adjustment num in 2nd Rocker	2.17	4.83	3.83	6.33	3.00	0.74	**0.004**
Adjustment num in 3rd Rocker	0.17	0.17	0.17	3.50	5.17	0.34	**< 0.001**
Adjustment num in Swing Phase	2.50	1.00	2.50	1.50	1.67	0.19	**< 0.001**

Note: TTU: tibia tuberosity; LML: lateral malleolus; CCL: dorsal calcaneus; DMT2: distal 2nd metatarsal; HLX: hallux.

No significant interaction was found but Figure 4 showed adjustments greatly occurred during the 2nd rocker phase.

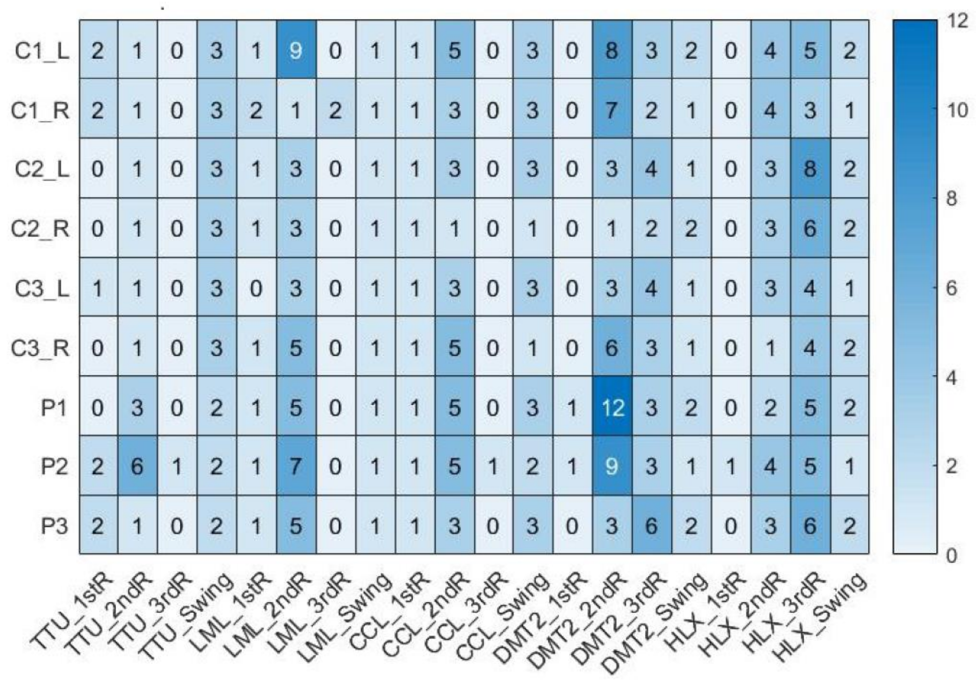

Figure 4. A grid displays number of foot and ankle adjustments measured by the count of valley and peak velocities for each participant over different rockers and phases. L: left, R: right, 1stR: 1st rocker phase, 2ndR: 2nd rocker phase, 3rdR: 3rd rocker phase, swing: swing phase. The value in grid is the number of adjustments.

DISCUSSIONS

Our research hypotheses are supported by our results. Specifically, patients with ligament injuries decreased stride length and increased stride duration as compared to control subjects. Patients increased maximum and minimum velocity in majority segments (including knee, ankle, hindfoot, midfoot and forefoot) during the gait cycle. We also observed significant changes during gait, especially in the 2nd rocker phase.

We are not surprised to see patients with ligament injuries walk with relatively small steps and quickly shift their weight to the side of health leg. Further examining the gait cycle found significant differences occurred during the 1st and the 2nd rockers, where patients had a short time to move body weight from the hindfoot to the forefoot (Table 3). This phenomenon was reported in other researches (19, 20). Ligaments injuries surrounding the ankle may be the root cause of the speedy weight-bearing shifting. When the calcaneus touches the floor during the early phase of stance, the musculoskeletal structure on the foot and ankle is taking force and loads immediately; ligaments surrounding the ankle needs to work coordinately to provide stable support. In the case of LCL injuries of ankle, such coordination may be destroyed partially. This may explain what micro-adjustments were observed in patients during the stance phase, presenting by increasing the number of adjustments in the velocity profiles during the 1st and the 2nd rockers phase (Table 5).

An increasing number of foot adjustments on the stance phase was a new finding for the patients suffering from LCL injuries of ankle. To our knowledge, no other similar evidence has been reported in those micro-adjustments in past literature. Considering this finding was revealed from our group of patients who repeatedly twisted their ankles and requiring surgical intervention, we propose this is kinematic evidence that can be used for explaining why some patients frequently twist their ankles after the first occurrence. Uneven terrains or unexpected interference during early phase of stance may overlap on to a micro-adjustment of the foot then lead to another ankle twist.

Another interesting finding was the different velocity profiles of patients during the early swing phase. As shown in Figure 3, patients displayed lower velocity compared to control subjects, especially from mid- and forefoot (Figure 3, 4th and 5th row). In the meantime, the knee velocity profiles of the patient were similar to the control subjects during the swing phase (Figure 3, 1st row). This piece of evidence suggests that the velocity reduction of subtalar joint during foot lifting in the early swing phase is to protect the lateral collateral ligament injured ankle.

Implications

Tracking kinematics of lower legs we can examine the differences of velocity and adjustment in shank and foot between patients with LCL injuries of ankle and control subjects. Kinematics features can further assist surgeons to make a patient-special treatment plan. For example, knowledge learned from the micro-adjustment of this study prompts an idea of designing a protection mechanism during the early stance phase, such as special cushion to elevate force and loads after the calcaneus touching the floor. We can also use micro-adjustment as a measure to assess the outcome of surgical intervention. We predict a satisfactory surgical treatment should help to reduce pain caused by the injured ligament and rebuild coordination among ligaments surrounding the ankle. As a result, the foot can bear loads as a stable unit without performing an increasing number of adjustments during weighing shifting from the hindfoot to the forefoot.

On the viewpoint of foot and ankle analysis, using the HFMM seems to be appropriate for investigating the pathological state of ligament injuries. Moreover, HFMM can support future temporal-spatial analysis for multiple foot and ankle motion patterns. By analyzing gait patterns in the future from big data will help us identify a pattern of ligament injuries and be applied to intelligent diagnosis for the patients with lateral ankle ligaments injury, which can automatically, accurately and immediately detect the injuries in acute phase and rehabilitation process (21, 22).

Detailed description of kinematic features as we did in this study can also improve our future attempt of identifying a pattern of ligament injury using artificial intelligent technology (23). Multi-segment three-dimensional motion data collected by the HFMM can be analyzed by machine learning/deep learning algorithms. In the future, the specific features based HFMM can support intelligent diagnosis and provide treatment consultation to patients with ligament injuries based on their gait kinematic differences.

Study limitations

Several limitations of the current analysis need to be mentioned. The first limitation came from our participants. Patients and control subjects consisted of young males only, which limits the generalizability of our findings to other populations. Needless to say that the number of patients needs to be increased in the future. The second limitation was the task included in the study. Participants were only asked to walk in a flat surface without adding stairway as most other kinematics studies had [24, 25]. The finding from the walking analysis cannot refer to other types of movements. To the extent possible, limitations are mitigated by the consistencies between the cohorts, methods, and variables compared between patients with LCL injuries of ankle and the normal participants.

CONCLUSIONS

In conclusion, our findings have demonstrated that patients with LCL injuries of ankle have shorter stride length, slower stride in gait cycle and more complex micro-adjustments in the 2nd rocker phase than in other rocker/swing phases during natural walking. Our findings revealed the human motion compensatory mechanism. Patients with ligament injury need more musculoskeletal adjustments to keeping body balance than normal. Precise descriptions of the kinematics are crucial for clinical assessment before and after surgical management. These results will also provide a foundation for computer-aided diagnosis in the future.

ABBREVIATIONS

CCL: dorsal calcaneus; **DMT1/2/5:** distal end of 1st/2nd/5th metatarsal; **HFMM:** Heidelberg Foot Measurement Model; **HLX:** hallux; **LCL injuries of Ankle:** lateral collateral ligament injuries of ankle; **LCL:** lateral medial calcaneus; **LEP:** lateral epicondyle; **LML:** lateral malleolus; **MCL:** medial calcaneus; **MEP:** medial epicondyle; **MML:** medial malleolus; **NAV:** navicular; **PMT1/5:** proximal end of 1st5th metatarsal; **SH1/2:** two points on the medial side of the shin; **TTU:** tibia tuberosity; **TV_{max}:** time to maximum velocity; **TV_{min}:** Time to minimum velocity; **V_{max}:** maximum velocity; **V_{min}:** minimum velocity; **3D:** three-dimensional.

DECLARATIONS

Ethics approval and consent to participate

The research has been approved by the Medical Scientific Research Ethics Review Committee of Peking University Third Hospital and each participant provided written consent before they enrolled in the study.

Consent for publication

The person’s data containing in this manuscript has consented for publication from the participates.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

All contributed to planning of experiments and interpretation of data. XL and BZ analyzed the data and wrote the manuscript. XL and QG designed the study and collect data. XL and DZ calculated the velocity profile. ZZ pre-processed the data and revised the manuscript. All authors read and approved the final manuscript.

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Figures

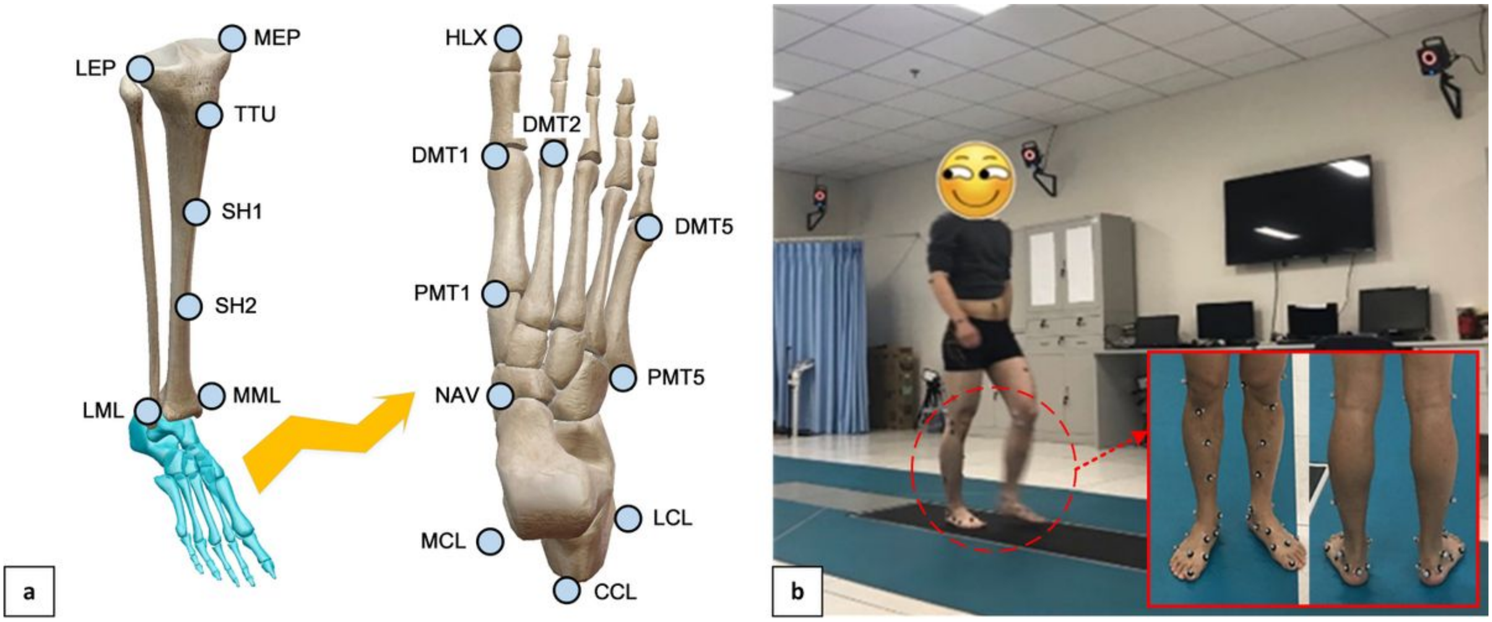

Figure 1

(a) Marker placement based on HFMM. LEP/MEP: lateral/medial epicondyle; TTU: tibia tuberosity; SH1/2: two points on the medial side of the shin; LML/MML: lateral/medial malleolus; LCL/CCL/MCL: lateral/dorsal/ medial calcaneus; NAV: navicular; PMT1/PMT5: proximal end of 1st5th metatarsal; DMT1/2/5: distal end of 1st/2nd/5th metatarsal; HLX: hallux. (b) Tracking movement of subjects by Vicon MX Motion Capture System.

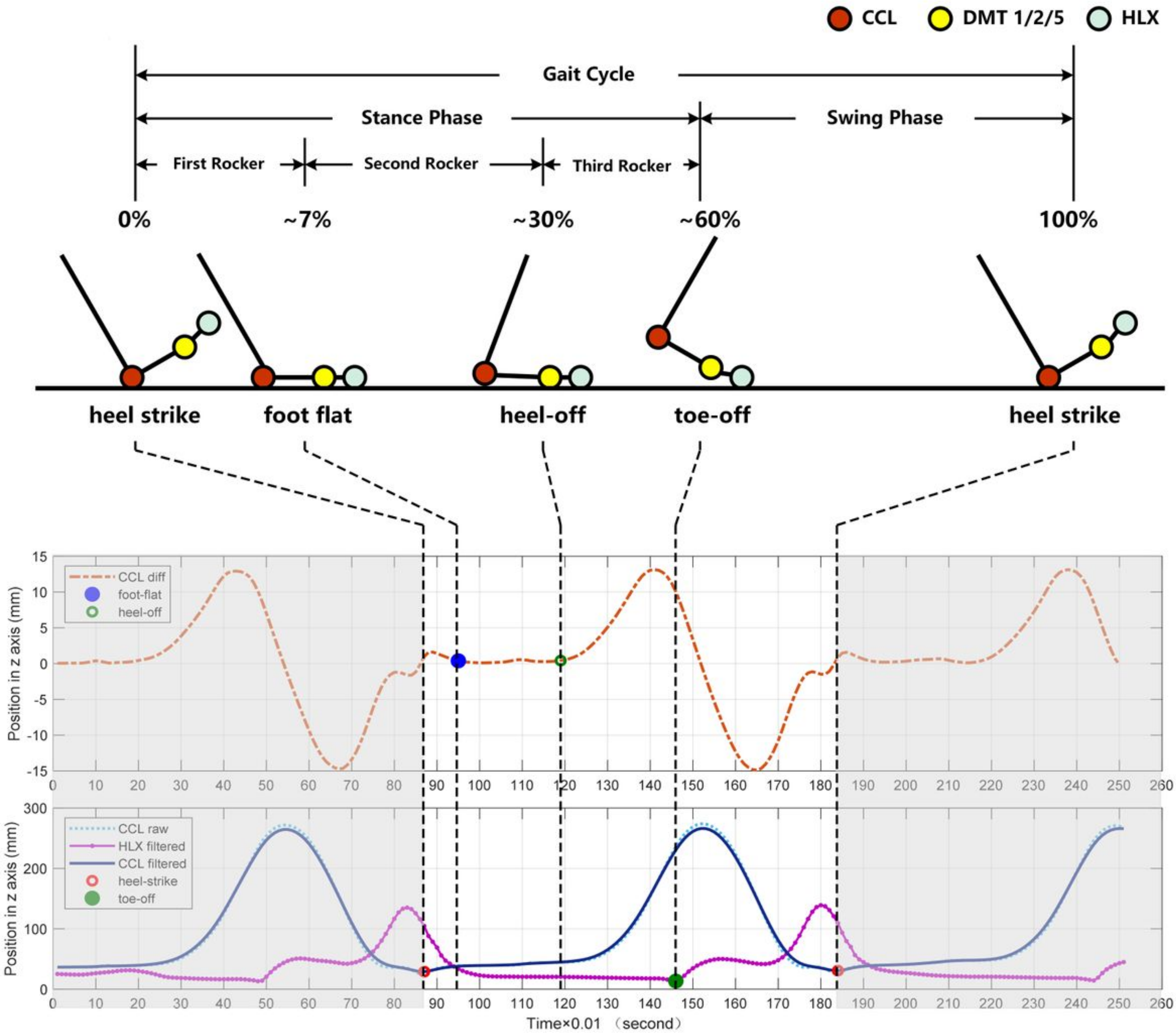

Figure 2

Gait cycles, phases and rockers splitting.

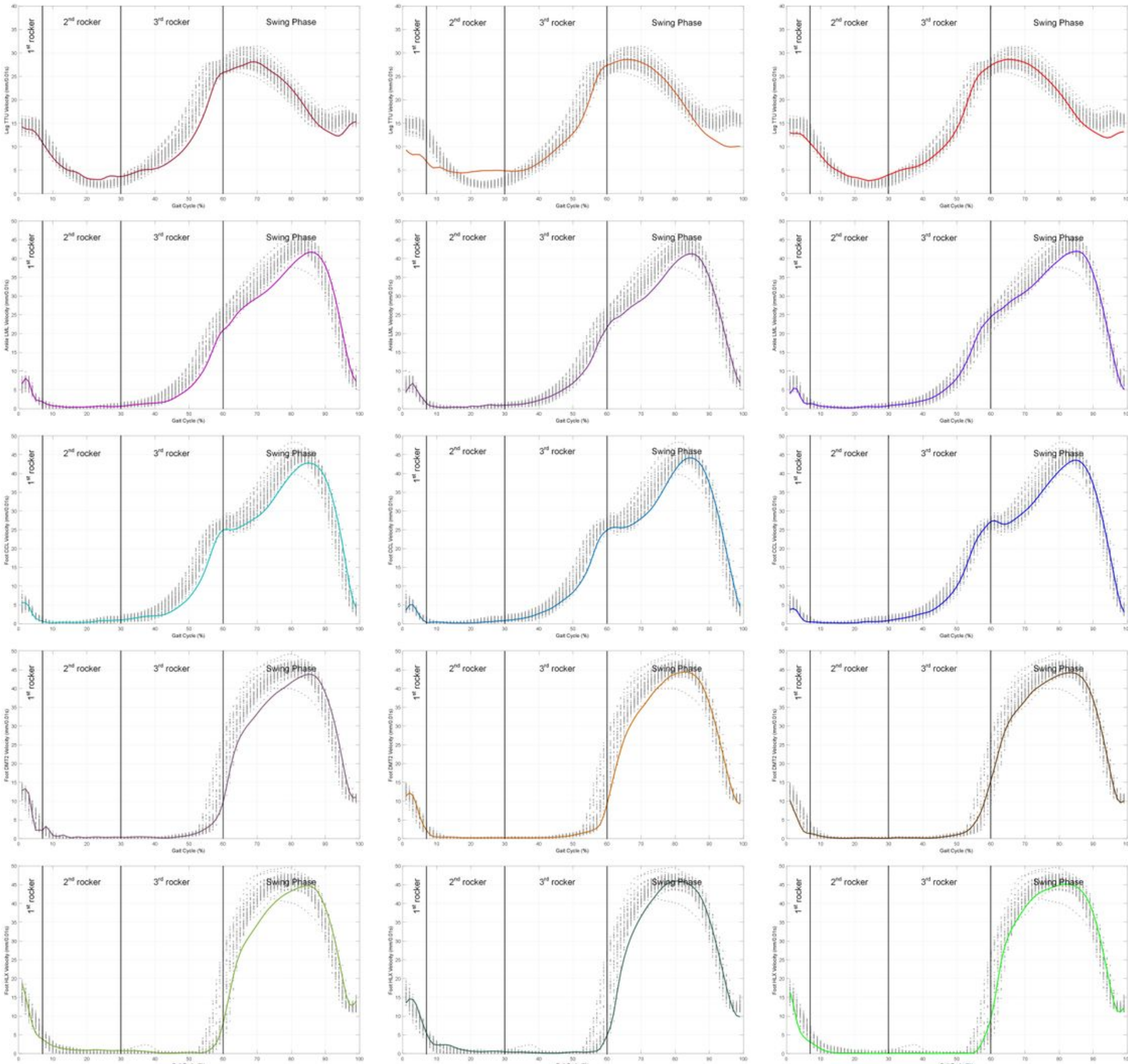

Figure 3

Velocity profiles of five anatomic landmarks (in row, marked by five sensors; TTU, LML, CCL, DMT2, HLX) over entire gait cycles of three patients (in column). Please noted that each gait cycle is normalized in time and the phases are separated by three long vertical lines. On each marker, the mean velocity profile (solid lines) over ten strides of patient are displayed on top of fifty velocity curves (grey dots) taken from three normal participants. As shown in Table 4, Vmax is significantly different in all five markers between patients and control subjects; basically, patients' maximum velocity is higher than the control subjects. The TVmax also display significant differences in all markers except for the TTU; specifically, patients reach peak velocity later than control subjects. The Vmin displays a significant difference only for the TTU, LML, DMT2. In these markers, Vmin is higher in patients than in control subjects. The TVmin only shows significance on the TTU marker, where control subjects reach to minimum velocity later than patients.

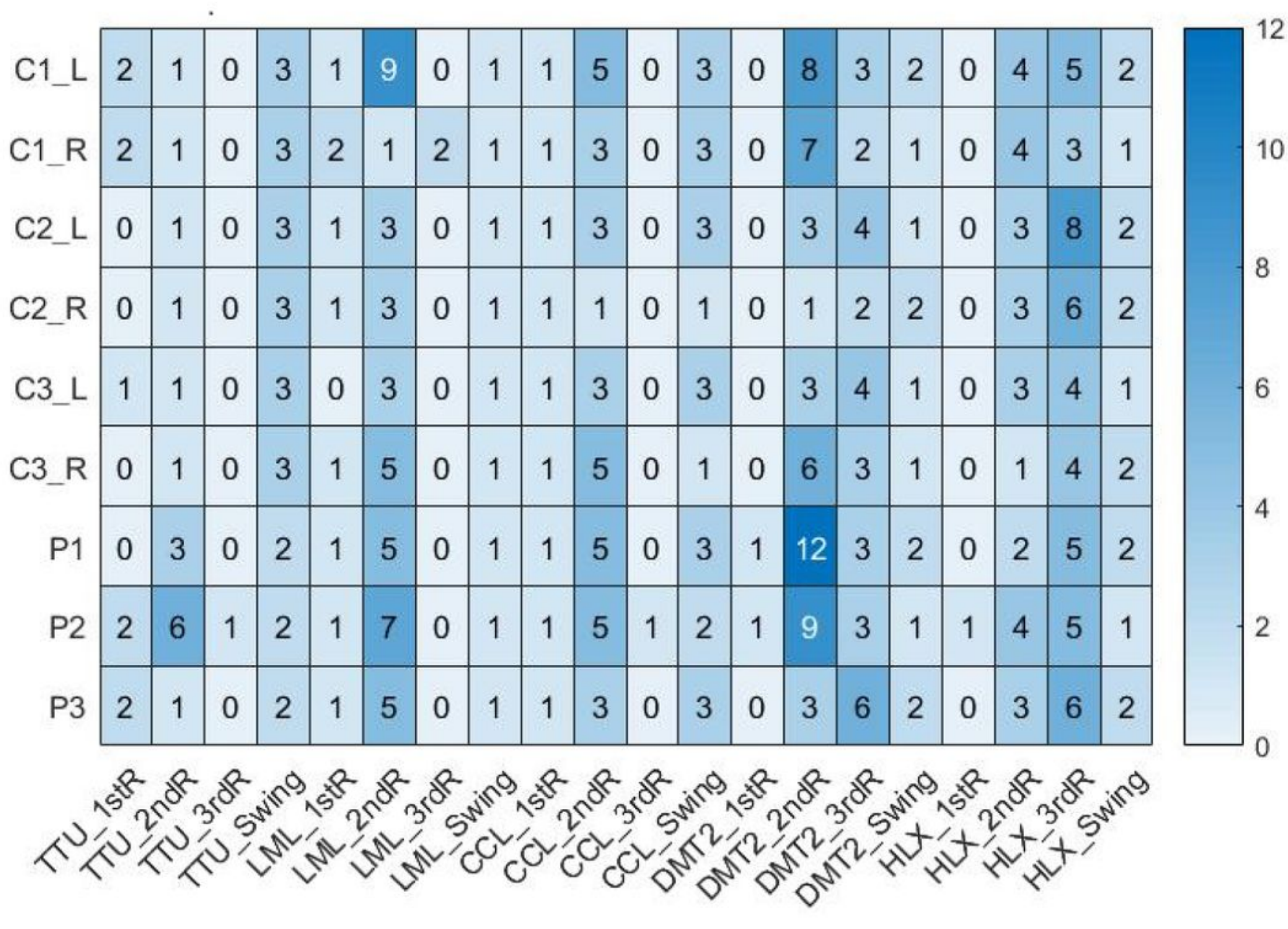

Figure 4

A grid displays number of foot and ankle adjustments measured by the count of valley and peak velocities for each participant over different rockers and phases. L: left, R: right, 1stR: 1st rocker phase, 2ndR: 2nd rocker phase, 3rdR: 3rd rocker phase, swing: swing phase. The value in grid is the number of adjustments.