Ankle and knee joint coordination in sagittal plane during kendo strike-thrust motion in healthy kendo athletes

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B Data Collection
C Statistical Analysis
D Manuscript Preparation
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Abstract

Background & Study Aim: Joint coordination patterns during sports movements are believed to be related to sports performance and injury risk. The objective of this study was to quantify joint co-ordination by using modified vector coding analysis and identify the individual co-ordination pattern of the left ankle and knee joint during kendo strike-thrust motion in healthy experienced kendo athletes.

Material & Methods: Fifteen experienced collegiate kendo athletes (age 20.4±1.2 years; height 171.5±4.0 cm; weight 73.9±9.1 kg; kendo experience 11.1±3.1 years) volunteered to participate in the study. Three-dimensional kinematic data was collected while participants were performing three sets of kendo motions at distances of 2 m from the target. We averaged the joint angle data and then used modified vector coding analysis to identify inter-segment co-ordination patterns during the single support phase of the kendo strike-thrust motion.

Results: We observed an '*N*-shaped' co-ordination pattern in seven participants, whereas we observed a '*topped-hat*' co-ordination pattern in seven other participants during the single support phase in the kendo strike-thrust motion. One participant presented a unique co-ordination pattern which could not be defined. In addition, the ratio of each joint co-ordination pattern varied among the kendo athletes.

Conclusions: We identified two distinct joint co-ordination patterns of the left knee and ankle joints during the single support phase of the kendo strike-thrust motion, '*N*-shaped' and 'topped-hut' patterns,. The stress applied to the lower extremity might be different between the two joint co-ordination patterns.

Key words: martial arts • lower extremity • kinematics • Achilles tendon prevention

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BACKGROUND

In kendo, regardless of their dominant leg, most athletes place their left foot behind their right foot while holding and pointing a bamboo sword with both hands ('*Shinai*') during the basic posture ('*Chudan no Kamae*'). They then execute repetitive strike-thrust motions against a specific part of an opponent's body (wrists, body or top head) with rapid forward leaps ('*Datotsu*'). During this motion, the lower right extremity functions as the leading limb, whereas power is derived from the left lower extremity [1].

In order to perform quick explosive sports motions such as kendo strike-thrust, one must effectively utilise stretch-shortening cycle (SSC) [2–5] and energy transfer from

Kendo – It literally means 'Way of The Sword'. Kendo is a modern Japanese martial art using bamboo swords (Shinai) and protective armour.

Shinai – a bamboo sword that is a safer replica of the Japanese sword

Chudan no Kamae – Chudan no kamae is the fundamental posture for kendo. In the chudan no kamae, the right foot is placed at slightly forward to the left foot. In addition, the knee of the right leg is slightly bent, whereas the left knee is straitened but no locked. The left heel is up about 2 cm off the floor. The tip of the shinai is pointed towards at the opponent's throat.

one joint to another [6]. A recent study of Koshida et al. [7] evaluated the joint angle curve of the left lower extremity during the single support phase (i.e. the phase between right foot-off and left foot-off) in the kendo strike-thrust motion. The results revealed that the left ankle dorsiflexion angle was approximately 20° on an average at the beginning and remained the same or slightly increased during the first half of the single support phase, followed by rapid ankle plantar flexion in the later phase. In contrast, the mean knee flexion began to increase at the beginning of the phase and reached its peak value shortly before the ankle dorsiflexion reached its peak as well. This result suggested that experienced kendo athletes might be capable of maximising SSC action using a complex sequence of ankle and knee movements rather than by using them in a simple simultaneous manner. Although qualitative analysis of each joint-angle curve has provided insight on lower extremity biomechanics which might be related to kendo performance, we require a quantitative analysis to further understand the inter-segmental motion of the knee and ankle joint [8].

Furthermore, previous studies have suggested that abnormalities of joint co-ordination might be partly related to injury occurrence [9–13]. Although kendo is believed to be a low injury risk sport, the number of Achilles tendon (AT) injuries is relatively high among these athletes [14-16]. The aetiology of AT injury is still a matter of debate; however, it is clinically accepted that the rapid alternation of the eccentric and concentric muscle actions of triceps surae plays an important role in the incidence of AT injury [17,18]. As the tension force applied to AT is affected not only by the ankle joint but also by the inter-segmental relationships between the knee and ankle joints because of the gastrocnemius muscle [6], quantifying the interactive pattern of ankle and knee joints during the kendo strike-thrust motion might also help us to understand further the cause of AT injury in kendo athletes.

Inter-segment joint co-ordination has been quantified by the relative excursion or similarity in temporal transition of two joint motions involved; however, these analyses provide the only data which represent the average joint co-ordination and the similarities in two joint curves, respectively [19,20]. Therefore, researchers have quantified inter-segment coordination of the lower extremity during basic athletic activities such as walking [21–23], running [19,20,24] and jumping [25], by using vector coding analysis, which was first introduced by Sparrow et al [26]. In addition, Chang et al. [22] proposed a new method to analyse the joint co-ordination pattern by coupling angles of the two joints so that the readers can visualise the complex sequence of joint co-ordination. The objective of this study was to quantify joint co-ordination by using modified vector coding analysis and identify the individual co-ordination pattern of the left ankle and knee joint during kendo strike-thrust motion in healthy experienced kendo athletes. Furthermore, we aimed to analyse the individual differences in joint co-ordination pattern between experienced kendo athletes during the strike-thrust motion.

MATERIAL AND METHODS

Participants

Fifteen male collegiate kendo athletes (mean ±SD; age 20.4±1.2 years; height 171.5±4.0 cm; weight 73.9±9.1 kg; years of kendo experience 11.1±3.1 years) participated in the study. To be eligible, the participant had to be without any history or current symptoms of significant injury. In addition, all the participants had no significant abnormalities of static alignment of the lower extremity. Before beginning the study, all the participants provided written informed consent. The study protocol was approved by the Ethics Committee of the Faculty of Health Sciences, Ryotokuji University, Chiba, Japan.

Experimental procedure

We assigned a set of 29 markers, which were developed by Kadaba et al. [27] (Helen Hayes marker set), on the bony landmarks of the participants to define individual body segments and their three-dimensional motion. Seven segments of the lower limbs were determined by the anterior superior iliac spines, sacrum, thighs, shins, ankles, toes and heel markers. In addition, we placed shoulder markers, elbow markers, wrist markers, a scapular marker, and three head markers to define these upper body segments. After the data from the static trial was collected and the joint centres identified, the medial knee and ankle markers were removed so that the motion of the lower extremity would not be disturbed by the markers during the task.

The experimental protocol included three sets of the kendo strike-thrust motions. First, the participants maintained the normal upright posture of kendo with the left foot placed on the force platform as the starting position; thereafter, they executed the kendo strike-thrust motion with a single forward leap toward the target which was adjusted to each participant's height with their utmost effort. During the task, the participant wore tight-fitting spandex shorts and used a bamboo sword '*Shinai*' which was officially approved by the All Japan Kendo Federation (length: 1.2 m, weight: 510 g).

We obtained three-dimensional (3D) marker trajectory data of kendo strike-thrust motion (150 Hz) with a Mac3D eight-camera motion analysis system (Motion analysis

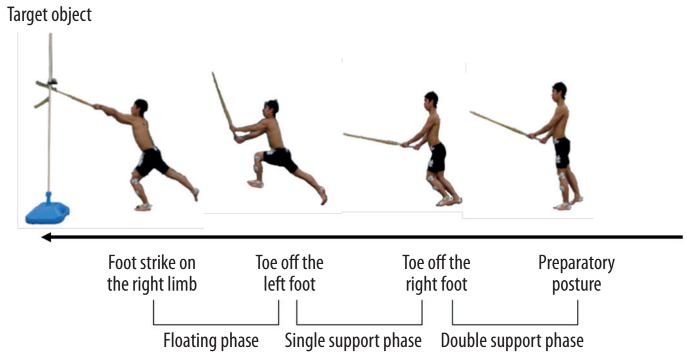

Figure 1. The temporal events and the phase of the kendo srtike-thrust motion.

Corp., Santa Rosa, CA, USA). Subsequently, marker trajectory data were filtered with the Butterworth low-pass filter at a 6 Hz cut-off frequency. We conducted data reduction and processing with a video processor/computer system (Eva software, Version 5.04, Motion analysis Corp., Santa Rosa, CA, USA) and clinical gait measurement system (OrthoTrak 6.03, Motion analysis Corp., Santa Rosa, CA, USA). In addition, we obtained 3D force data with a force platform as well (Anima Corp., Tokyo, Japan).

Data analysis

Because the majority of the AT injuries occur on the left limb in kendo, it is reasonable to focus on the lower extremity biomechanics of the left side [7]. We divided the strike-thrust motion into three phases, as defined by the synchronised force data: from starting position to right foot-off as the double leg support phase, from right foot-off to left foot-off as the single leg stance phase and from left foot-off to right foot-strike as the floating phase (Figure 1). In this study, joint angles the left ankle flexion-extension and knee flexion-extension during the single support phase were computed. The kinematic data were normalised into 100 frames.

The averaged data of the knee and ankle angle-time curves was used for modified vector-coding analysis (Figure 2). We calculated coupling angles (CA) by using the formula given below [24]:

$$CA_i = \tan^{-1}\left(\frac{y_{i+1}-y_i}{x_{i+1}-x_i}\right),$$

where $0^\circ \le CA_i < 360^\circ$, *y: ankle joint angle, x: knee joint angle, i=0,1,2,…,99*

CA ranging from 0° to 90° indicates that ankle dorsiflexion and knee flexion increased simultaneously, whereas CA ranging from 180° to 270° indicates the opposite action. In contrast, CA ranging from 90° to 180° indicates that the ankle and knee joint increased the dorsiflexion and extension angles respectively, whereas CA ranging from 270° to 360° indicates the opposite action.

We calculated the percentage of each joint co-ordination pattern during the strike-thrust motion, which was defined as follows: ankle dorsiflexion–knee flexion (DF–KF) pattern ($0^\circ \le CA < 90^\circ$), ankle dorsiflexion–knee extension (DF–KE) pattern ($90^\circ \le CA < 180^\circ$), ankle plantar flexion-knee extension (PF–KE) pattern ($180^\circ \le CA < 270^\circ$) and ankle plantar flexion-knee flexion (PF–KF) pattern ($270^\circ \le CA < 360^\circ$; Figure 2). In addition, we analysed the individual continuous CA curve of ankle and knee joint co-ordination pattern using a qualitative approach.

Results

Figure 3 demonstrates the mean (± standard deviation; SD) angle-time curve of the ankle and knee joints during the single stance phase of the kendo strike-thrust motion. Mean range of motion of ankle and knee joints during the stance phase were 48.2±8.2° and 28.6±4.6°, respectively. Finally, mean duration of this motion was 0.34±0.07 s.

Figure 4 shows the individual CA curves of all the participants. We identified two distinct patterns in the CA angle curves. The CA angle curves of the seven participants A, B, D, G, H, I and O exhibited an '*N*-shaped' curve, whereas the CA angle curve in another seven participants, C, E, F, J, K, L and M, exhibited a '*topped-hat*' shaped curve. We categorized the participant N as '*miscellaneous*' because the CA curve did not match the defined characteristics of either pattern.

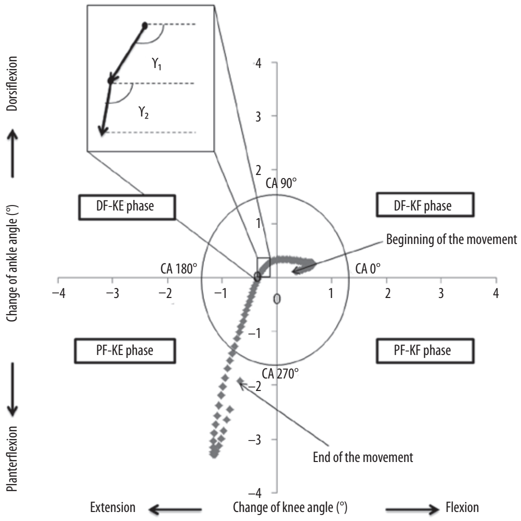

Figure 2. Modified vector coding analysis and the definition of the joint co-ordination pattern: CA – coupling angles, DF – ankle dorsiflexion, PF – ankle planterflexion, KF – knee flexion, KE – knee extension.

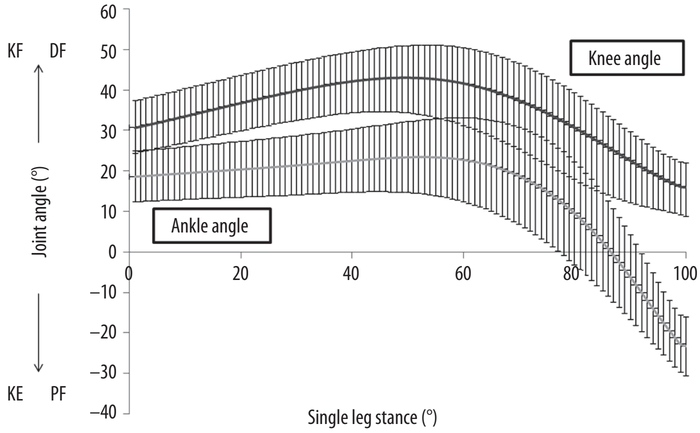

Figure 3. Mean (±SD) joint angle-time curves of knee and ankle joints during the single support phase in the kendo strike-thrust motion: DF – ankle dorsiflexion, PF – ankle planterflexion, KF – knee flexion, KE – knee extension.

Figure 5 shows the individual percentage data of the four joint co-ordination patterns. It appeared that left ankle and knee joint co-ordination during the single stance phase in the kendo strike-thrust motion mostly consisted of a DF–KF and PF–KE pattern, although the ratio of both patterns varied among individuals. DF–KE and PF–KF patterns were not always observed in the participants: DF–KE pattern was only observed in participants A, B, D, G, H, I and O, whereas PF–KF pattern was only observed in participants C, D,E, F, J, K, L and M. However, neither DF–KE nor PF–KF patterns were observed in the participant N.

DISCUSSION

Understanding joint co-ordination during athletic movements is fundamental in gaining a full insight into athletic performance enhancement [28,29] and overuse injury prevention [9,24]. A previous study by Koshida et al. [7] suggests that the ankle and knee joint co-ordinate with each other in a complex manner and play a key role in kendo performance and injury prevention. However, the data regarding joint co-ordination patterns in the lower extremity during kendo motions is very limited. Therefore, in this study, we aimed to quantitate joint

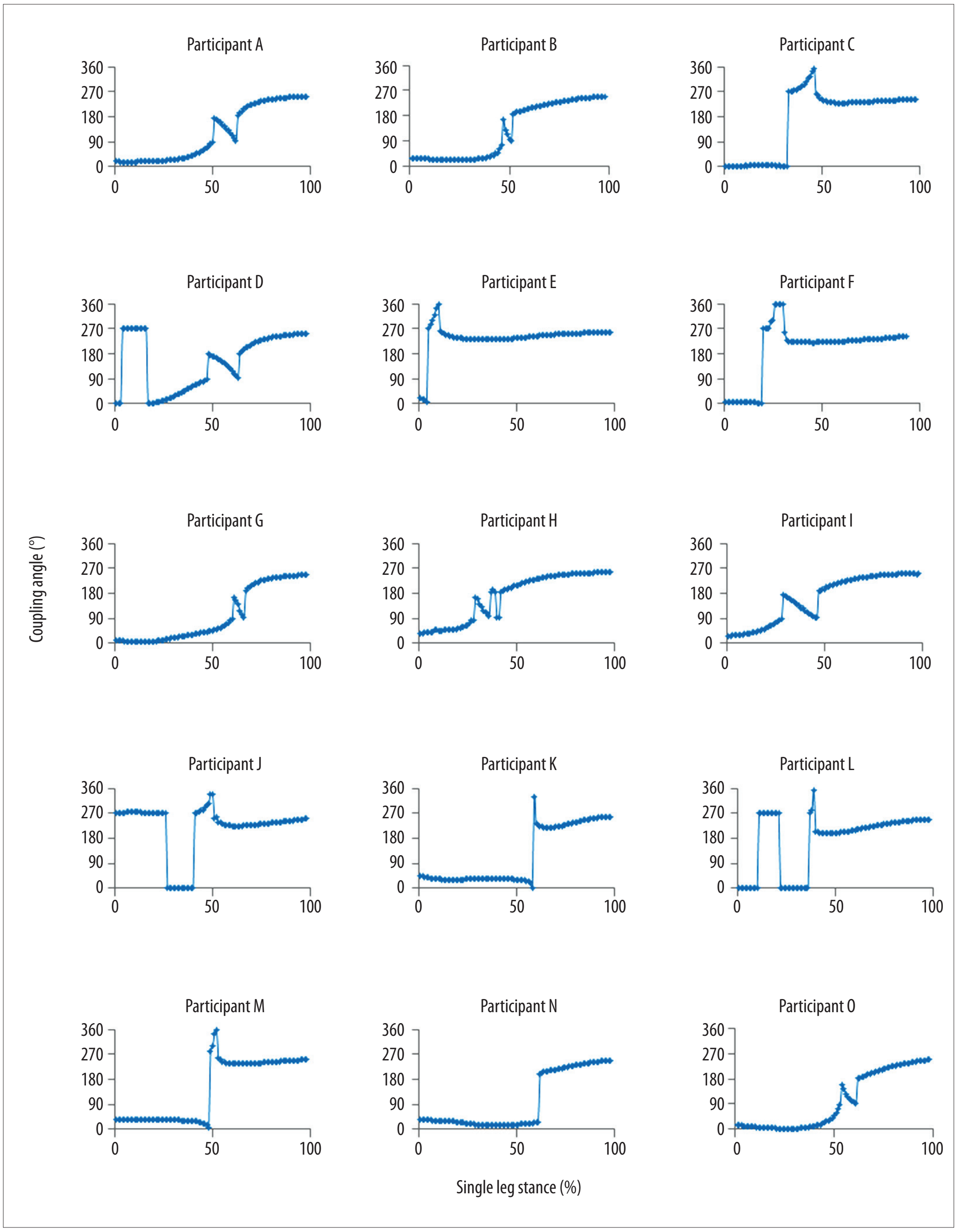

Figure 4. Coupling angle curves of each participant during the kendo strike-thrust motion.

co-ordination patterns in uninjured kendo athletes to provide reference data for future studies.

The kendo strike-thrust motion is quick and explosive and thus needs to utilise SSC consisting of an eccentric phase, transition phase and concentric phase [30]. In most of the individual CA time curves, we observed similar patterns of joint co-ordination. First, DF–KF pattern (i.e. CA <90°) was observed as eccentric phase and transition phase, which was determined by abrupt changes in the joint co-ordination curve in the early to middle stance phase; this was followed by PE-KE pattern (i.e. 180° ≤CA <270°), which indicates the concentric phase which produces the propulsive force for an effective kendo strike-thrust motion. In contrast to the other SSC phases, the joint co-ordination pattern during the transition phase varied among the participants.

The individual profiles of the CA time curve and histogram indicated that there were two different strategies of joint co-ordination in the transition from the eccentric to the concentric phase in the kendo motion. We identified one

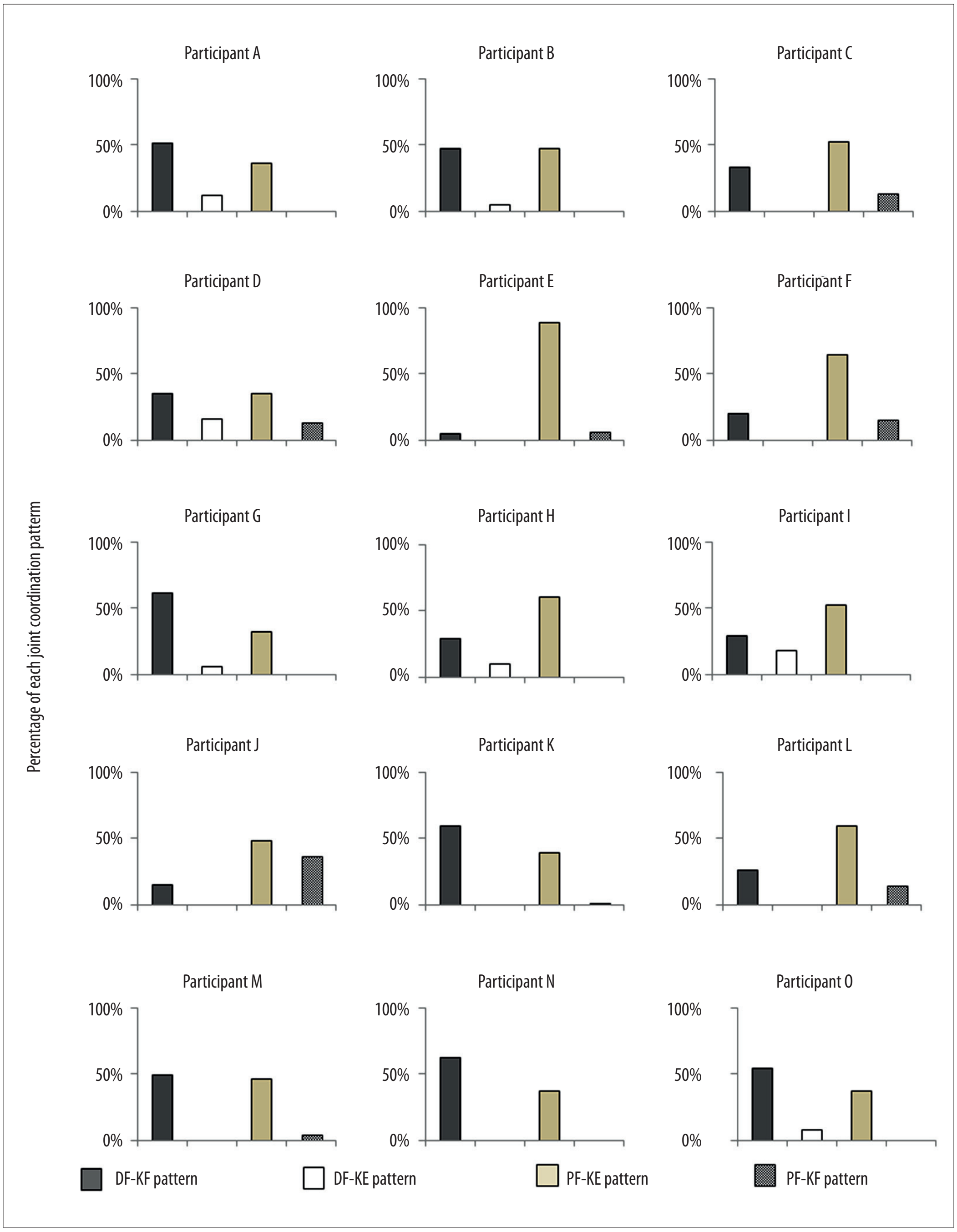

Figure 5. Percentage data of joint coordination types of each participant during the kendo strike-thrust motion: DF – ankle dorsiflexion, PF – ankle planterflexion, KF – knee flexion, KE – knee extension.

joint co-ordination pattern characterized by an '*N*-shaped' transition in seven participants. The transition pattern indicates simultaneous ankle dorsi-flexion and knee extension (i.e. 90° ≤CA <180°) during the transition. Because the gastrocnemius muscle crosses both knee and ankle joint, and its tension might be influenced by the actions of both the joints, we speculate that the inter-segment relationship must have increased the tension force and also enabled the elastic energy to be stored in the triceps surae muscle-tendon complex. This would have helped the athletes to exert the explosive force to the floor in the late single support phase of the kendo motion. The second prominent joint co-ordination pattern was characterized as a '*topped-hat*' shape curve, which was observed in another seven kendo athletes in this study. The shape of '*topped-hat*' curve represents the simultaneous movements of ankle plantar flexion and knee flexion (i.e. 270° ≤CA <360°). This joint co-ordination pattern during the transition phase might act to increase the stiffness of the ankle joint, thereby helping to produce a propulsive force during the push-off phase [31].

Previous studies have reported that even if the stress imposed on AT is within its physiological limits, the repetitive non-uniform stress from different individual force contributions of the gastrocnemius and soleus will cause micro-trauma in AT, leading to overuse injury [32]. In addition, previous studies have reported that the discrepancy of the stresses imposed on AT between gastrocnemius and soleus muscle was attributed to knee flexion angle during muscle contraction [33,34]. Therefore, the joint co-ordination pattern between ankle and knee joint angles during the kendo strike-thrust motion provide more data regarding AT injury in kendo athletes. As we described, the '*N*-shaped' transition indicating ankle dorsi-flexion and knee extension is thought to produce the greatest tension force on the gastrocnemius muscle. Although the antagonistic motions might enhance the stretching of the triceps surae muscle–tendon complex for effective SSC action during the kendo strike-thrust motion, we speculate that the inappropriate duration and/or timing of the '*N*-shaped' transition, with or without malalignment of the lower extremity, might increase the risk of AT injury. However, further studies are required to confirm the relationship between AT injury and the joint co-ordination pattern.

Our participants were collegiate level athletes with no history of an AT injury which prevented them from attending kendo practice or matches for a significant period of time throughout their athletic career; thus, we can use these joint co-ordination patterns as a standard reference. In future studies, it will be interesting to investigate whether different knee–ankle joint co-ordination patterns are present in kendo athletes with different performance levels, including elites and novices, with/without a history of AT injury.

Previous studies have reported that runners with chronic AT injuries demonstrated greater ankle (sub-talar) eversion during the stance phase of running [35,36]. If greater eversion occurs in phases with high AT loading, it might result in chronic overuse AT injury. When considering the joint co-ordination pattern as a possible risk factor in AT injury, the joint co-ordination in other planes needs to be analysed as well.

We acknowledge some limitations of this study. The current study did not examine the actual tension force applied to AT during the kendo strike-thrust motion. Further studies are also necessary to elucidate the relationships between the joint co-ordination pattern and the level of performance in kendo as well as the incidence of AT injury. In addition, our findings were descriptive and provided only basic information regarding joint co-ordination in experienced kendo athletes. Kendo involves not only the strike motion with forward steps but also repetitive forward-backward bounding-like steps and directional changes, which might also alter knee-ankle joint co-ordination. Therefore, it will be necessary to include different kendo motions, involving forward-backward steps and directional changes in future experimental protocols. Finally, in the present study, no statistical tests were conducted, and further research with a larger sample size is required to confirm the results obtained in our study.

Conclusions

Our study presents preliminary information on the joint co-ordination patterns of left knee and ankle during the kendo strike-thrust motion in healthy experienced kendo athletes. We identified two common joint co-ordination patterns during the transition phase in the kendo strike-thrust motion, '*N*-shaped' pattern and the '*topped-hut*' co-ordination patterns. The '*N*-shaped' pattern is characterised as simultaneous ankle dorsi-flexion and knee extension, whereas the '*topped-hut*' pattern is characterised as the simultaneous movements of ankle plantar flexion and knee flexion during the transition phase. The different co-ordination patterns might expose the lower extremity of the athletes to the different tension stress pattern during the kendo strike-thrust motion.

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