Science & Sports 37 (2022) 51—57

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ORIGINAL ARTICLE

The effects of taekwondo shoes on anterior cruciate ligament injury risk factors during jump whip kicks

Les effets des chaussures de taekwondo sur les facteurs de risque de blessure au ligament croisé antérieur lors des coups de fouet sautés

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Received 22 October 2020; accepted 23 April 2021
Available online 20 January 2022

KEYWORDS
Taekwondo shoes;
Anterior cruciate ligament;
Injury risk factors;
Jump whip kick

Summary
Objectives. — This study aimed to investigate the effect of taekwondo shoes on anterior cruciate ligament injury risk factors in taekwondo athletes performing jump whip kicks.
Equipment and methods. — The participants comprised 10 taekwondo athletes with no history of anterior cruciate ligament or lower extremity injuries within the past 12 months. The maximum hip flexion angle, maximum knee valgus angle, maximum knee extension moment, maximum knee lateral rotation moment, and quadriceps and hamstring muscle activity ratios were analyzed using video, ground reaction force, and electromyography analysis systems.
Results. — The maximum knee valgus angle was significantly lower when wearing taekwondo shoes while performing taekwondo jump whip kicks ($p = 0.04$), and the activity ratio of the quadriceps and hamstring muscles was low ($p = 0.10$).

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https://doi.org/10.1016/j.scispo.2021.04.002

Conclusion. — Wearing taekwondo shoes had a positive effect on preventing anterior cruciate ligament injury; therefore, the importance of wearing taekwondo shoes should be communicated clearly to athletes and coaches to increase their frequency of use and change negative perceptions regarding taekwondo shoe use during training. Taekwondo competition movements can cause damage to the anterior cruciate ligament owing to sudden changes in direction and jump movements. Our results suggest that wearing taekwondo shoes can help prevent anterior cruciate ligament injuries.

MOTS CLÉS
Chaussures de taekwondo ;
Ligament croisé antérieur ;
Facteurs de risque de blessure ;
Coup de fouet

Résumé

Objectifs. — Cette étude visait à étudier l'effet des chaussures de taekwondo sur les facteurs de risque de blessure au ligament croisé antérieur chez les athlètes de taekwondo effectuant des coups de fouet sautés.

Équipement et méthodes. — Les participants comprenaient 10 athlètes de taekwondo sans antécédents de ligament croisé antérieur ou de blessures aux membres inférieurs au cours des 12 derniers mois. L'angle de flexion maximal de la hanche, l'angle maximal de valgus du genou, le moment maximal d'extension du genou, le moment maximal de rotation latérale du genou et les rapports d'activité des quadriceps et des ischio-jambiers ont été analysés à l'aide de systèmes d'analyse vidéo, de force de réaction au sol et d'électromyographie.

Résultats. — L'angle de valgus maximal du genou était significativement plus faible lorsque l'on portait des chaussures de taekwondo tout en exécutant des coups de fouet de taekwondo (p = 0,04), et le rapport d'activité des quadriceps et des muscles ischio-jambiers était faible (p = 0,10).

Conclusion. — Le port de chaussures de taekwondo a eu un effet positif sur la prévention des blessures du ligament croisé antérieur; par conséquent, l'importance du port de chaussures de taekwondo doit être clairement communiquée aux athlètes et aux entraîneurs pour augmenter leur fréquence d'utilisation et changer les perceptions négatives de l'utilisation des chaussures de taekwondo pendant l'entraînement. Les mouvements de compétition de taekwondo peuvent endommager le ligament croisé antérieur en raison de changements brusques de direction et de mouvements de saut. Nos résultats suggèrent que les blessures du ligament croisé antérieur pourraient être évitées en portant des chaussures de taekwondo.

1. Introduction

Today's elite sports athletes are excessively focused on improving performance, with injury prevention being a lesser priority [1]. Sports injuries reduce athletes' performances and have been reported to lead to unstable psychological conditions, which adversely affect their athletic lives [2]. In particular, anterior cruciate ligament injuries can lead to more serious sequelae than other types of injuries, often resulting in high treatment costs and long periods of rehabilitation [3].

Approximately 70% of anterior cruciate ligament injuries are attributed to non-contact injuries involving actions such as landing after jumping [3,4]. In particular, jump motions using rotation have a high risk of anterior cruciate ligament injury as the load transmitted to the knee and the rotational force act simultaneously upon landing [5]. According to one study on taekwondo injuries, most anterior cruciate ligament injuries occur during landing following an aerial kick [6].

There are several aerial rotation kicks, but the most common is the jump whip kick. During the jump whip kick action in taekwondo, damage to the anterior cruciate ligament can result from an athlete landing on one foot. Andrew et al. [7] also reported that one-footed landings are associated with a higher risk of forward cross ligament compared to two-footed landings. As a result, a one-footed landing carries a greater risk of injury to the anterior cruciate ligament.

After the adoption of an electronic protection system, extraneous foot skills were increasingly developed, as seen at the World Taekwondo Federation General Assembly on April 5, 2018. To further encourage various eye-catching foot skills, an additional point was added for the rotating kick technique, increasing from 1 point to 2 [8]. Without incorporating a rotating kick in a taekwondo competition, a team would be less likely to lead the competition.

As the frequency and use of high rotary kicks have increased during competitions and training, the incidence of anterior cruciate ligament injuries among taekwondo athletes has increased as more load is applied to the knee when landing [9]. Wearing taekwondo shoes may help prevent injuries during the taekwondo sport; however, studies investigating how taekwondo shoes prevent injury are limited. Jin and Kawk [10] reported that assessing simple running motions was ineffective in evaluating the efficacy of taekwondo shoes when landing after high kicking.

Early taekwondo shoe manufacture emphasized function and simple foot protection from external shocks rather than specific professional functionality [11]. Athletes and coaches seemingly have limited knowledge about the efficacy of taekwondo shoes, and some athletes still do not wear taekwondo shoes during training. Taekwondo shoes have subsequently been developed to enhance exercise functions and address functional issues such as the prevention of injuries that may occur during exercise [12]. Some studies have investigated improvements in the shock-absorbing capabilities of taekwondo shoes in relation to concerns raised in sports science and sports medicine [12]. Recent trends in the manufacture of taekwondo shoes have involved designs aiming to prevent anterior cruciate ligament injuries.

The risk of anterior cruciate ligament injury has been associated with the maximum hip flexion angle, maximum knee valgus angle, maximum knee extension moment, maximum knee lateral rotational moment, and activity ratio of the quadriceps and hamstring muscles, based on study findings by Hewett et al. [3] and Alentorn-Geli et al. [4].

This study aimed to analyze the effects of taekwondo shoes in preventing anterior cruciate ligament injuries while performing a jump whip kick action when wearing either two types of taekwondo shoes, namely, shoes similar to the most commonly used Nike products or the most recently developed taekwondo shoes, or when performing the jump whip kick action while barefoot. This study further aimed to investigate the efficacy of wearing taekwondo shoes in preventing anterior cruciate ligament injury among taekwondo athletes specifically in relation to the identified risk factors.

2. Methods

2.1. Participants

Ten males professional taekwondo athletes from the Department of Taekwondo at our university with >10 years of taekwondo competition experience participated in this study. Participants had a mean 13 ± 3 years of athletic experience, mean age of 24 ± 4 years, mean height of 173.3 ± 8.5 cm, mean weight of 64.2 ± 12.5 kg, and shoe size ranging from 250—260 mm. Inclusion criteria comprised no previous history of anterior cruciate ligament injuries and no history of lower extremity injuries within the last 12 months. Furthermore, to standardize the athletes in terms of kicking practice, only participants who were right-foot dominant were selected. This study was approved by the Chung-Ang University Institutional Review Board.

2.2. Experimental procedure

Participants received a verbal explanation of the overall experimental process and precautions, including the purpose of the experiment and the experimental procedure. To perform the experiment consistently when performing barefoot kicks, participants were advised not to kick to the point where injury to the feet could occur. After providing informed consent, the participants changed into short tights, which were part of their experimental clothing. To adapt to the test site environment, the participants were familiarized with the location of the test equipment and provided with precise details concerning the two aerial kicking motions. Warm-up exercises and a set of two stretching exercises were then performed to allow the participants to perform more accurate movements. After demonstrating the two aerial kicking motions that were to be performed during the experiment, the participants repeatedly practiced these kicking motions.

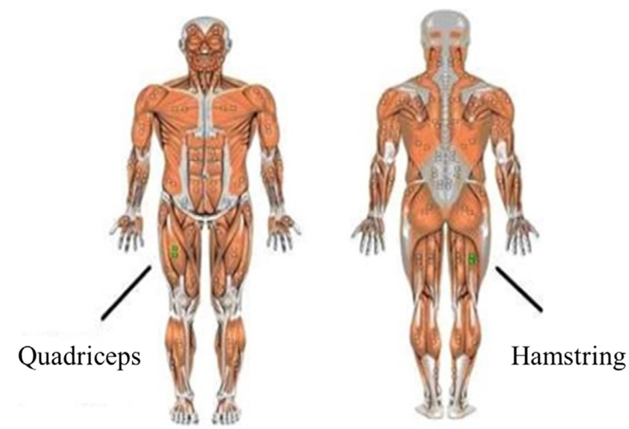

Figure 1 EMG electrode attachment site.

To increase the accuracy of the electromyography (EMG) data, EMG electrodes were positioned on the participants' quadriceps and hamstring muscles following hair removal and skin disinfection using alcohol (Fig. 1).

Before starting the experiment, maximum voluntary contraction (MVC) measures for the quadriceps and hamstring muscles were recorded using EMG.

To calculate the values of the kinematic variables that are risk factors for anterior cruciate ligament injury, reflective markers were attached to major parts of the bodies of the participants and their taekwondo shoes (Fig. 2).

Static imaging to estimate the human joint center point was performed for 5 seconds. At this time, the participants were required to assume an anatomical posture and were asked to remain motionless. After completing the static imaging, the participants began the experiment and performed the jump whip kick motion according to their rhythm while running in step. Participants performed five jump whip kick motions under three different conditions, namely, while wearing the two different types of taekwondo shoes and then while barefoot, and random data were collected. Two taekwondo shoe models were selected comprising a previously developed early taekwondo shoe model (model A) and the most recently developed taekwondo shoe model (model B) (Fig. 3). Model A shoes weighed approximately 180 g based on a 250 mm shoe length, and model B shoes weighed approximately 200 g (an approximate 20 g weight difference between the models). Both models were made of artificial leather, and the outsole design involved separate forefoot and rearfoot sections.

All hitting positions were standardized according to the height of a participant's face and the hitting position was fixed by setting a taekwondo mat as the hitting target. We did not record kicking motions and positions that were not accurate, or when participants fell on landing. Only motions that were successfully performed were recorded. Furthermore, the experiment was stopped any time a participant asked for a break. To minimize recording deviations due to

Figure 2 Marker attachment site.

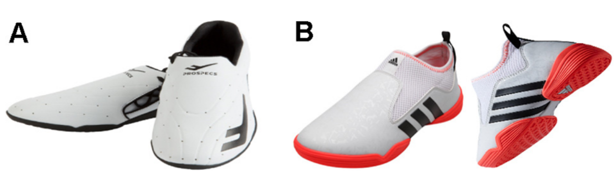

Figure 3 Taeswondo shoes model A (left) and model B (right).

fatigue, the kicking motions were performed after sufficient rest.

2.3. Data processing

EMG data processing was performed using a wireless EMG system (Telemyo DTS, Scottsdale, AZ, USA). For row EMG, a 10—350 Hz band pass filter was used, followed by full wave rectification. Subsequently, a smoothing operation was used as a root mean square (RMS) of 100 ms, and the measured EMG values were expressed as ratio values for each motion, based on the stored MVC measurement values. The activity ratio of the quadriceps and hamstring muscles was calculated as follows:

EMG ratio (%) = [quadriceps IEMG/(hamstring IEMG + quadriceps IEMG)] $\times$ 100.

The sampling rate of the infrared camera was set to 200 frames/sec. A non-linear transformation (NLT) technique was used for the three-dimensional (3D) coordinate calculation. When 3D coordinate values were calculated, rectification was performed using Butterworth 4th order low pass filter cut-off frequency 15 Hz filtering to remove errors due to noise. The dynamics method was used to calculate the knee joint moment. This method was applied through substituting information concerning force and displacement obtained from the motion analysis with ground reaction force measurement values in the motion equation. The calculated moment value was divided by the product of each participant's height and weight and standardized and analyzed to enable relative comparison. To remove noise from the ground reaction force measurement, a filtering Butterworth 4th order low pass filter cut-off frequency of 15 Hz was applied and rectified [12]. The analysis section was set from the moment the landing foot touched the ground to the moment when the knee was maximally flexed.

2.4. Statistical analysis

SPSS 20.0 software was used for statistical analysis. One-way repeated analysis of variance tests were conducted to analyze the effects on the anterior cruciate ligaments of 10 taekwondo athletes in terms of risk factors during jump whip kicking while barefoot and while wearing model A and model B taekwondo shoes. The Scheffe method was used for the post-analysis, and the level for verifying statistical significance was set at a P-value of 0.05.

3. Results

3.1. Maximum hip flexion angle

No statistically significant difference was found between actions performed barefoot and while wearing model A and model B shoes in terms of the maximum hip flexion angle.

3.2. Maximum knee valgus angle

In terms of the maximum knee valgus angle, there was a statistically significant difference between actions performed barefoot and while wearing model A and model B shoes ($P < 0.004$). Post-hoc analysis results showed that the maximum knee valgus angle while performing barefoot was significantly greater than when wearing model A shoes ($P = 0.013$) and model B shoes ($P = 0.012$). There was no statistically significant difference between actions performed wearing either model A or B shoes.

3.3. Maximum knee extension moment

No statistically significant difference was found in terms of the maximum knee extension moment between actions performed barefoot and when wearing model A and B shoes or between actions performed wearing either model A or B shoes.

3.4. Maximum knee lateral rotation moment

No statistical difference was found in terms of the maximum knee lateral rotation moment between actions performed barefoot and when wearing model A and B shoes or between actions performed wearing either model A or B shoes.

3.5. Activity ratio of the quadriceps and hamstring muscles

Concerning the activity ratio of the quadriceps and hamstring muscles, a statistically significant difference was found between the three levels ($P < 0.010$). Post-hoc analysis results showed a significantly higher quadriceps and hamstring muscle activity ratio when barefoot compared to when wearing model B shoes ($P = 0.011$). There was no statistically significant difference in the activity ratio between actions performed barefoot and wearing model A shoes, or between actions performed wearing either model A or B shoes (Table 1).

4. Discussion

The angle of hip joint flexion during landing has been reported to be a risk factor for damage to the anterior cruciate ligament [13]. As the hip angle increases during landing, the impact force transmitted to the knee increases [13,14]. Krosshaug et al. [14] reported that if the angle of flexion at the hip joint increases at the moment of landing following a jump action, the center of the body moves forward in proportion to the flexion angle. As the center of the body moves forward after landing, a greater tension in the anterior cruciate ligament is generated, which may result in an increased risk of injury. Boden et al. [13] analyzed videos containing 29 anterior cruciate ligament injuries that occurred during various sports activities. They found that increased hip flexion movements were common among injured athletes, which suggested this was a risk factor for anterior cruciate ligament injury. In our study, no statistically significant differences were observed in terms of whether the participants were barefoot or wearing either model A or B shoes while performing the jump whip kicks. This may have been because the characteristics of the sport in a taekwondo setting may have influenced the outcome. We consider that coordinated movements of the athlete in trying to quickly return to the upper body center of gravity occurred because follow-up movements must be continued immediately after kicking in an actual competition situation. Further studies are needed to investigate the movements occurring during a general drop landing jump motion and a vertical jump task not only the jump whip kick action performed by participants in this study.

The maximum knee valgus angle at landing is a known risk factor for anterior cruciate ligament injury [15,16]. Fukuda et al. [15] reported that as the knee valgus angle increased, the anterior valgus angle increased, and tension applied to the anterior cruciate ligament increased owing to an increase in the tibial push. Hewett et al. [16] reported that high-difficulty motion on the long axis leads to excessive valgus motion of the knee, which can result in anterior cruciate ligament rupture. The jump whip kick motion performed in this study is also a rotational motion occurring on the long axis and. As it is a motion accompanied by a jump, it could be seen as a motion with a high probability of anterior cruciate ligament injury. In our study, statistically significant differences were found in terms of the maximum knee valgus angle according to whether or not taekwondo shoes were worn during the jump whip kicks, with actions performed barefoot showing higher angles than those performed while wearing model A and model B taekwondo shoes. In a study that identified the effects of wearing gymnastic shoes on the anterior cruciate ligament, the maximum external angle was reduced by approximately 6 degrees compared with when gymnastic shoes were not worn [17]. In our study, taekwondo shoes reduced the angle approximately 4 degrees compared with the actions performed barefoot. Although the characteristics of the tasks performed in Lim et al.'s [17] study and our study were somewhat different, both gymnastic and taekwondo shoes showed smaller valgus angle values than barefoot valgus angle values. A decrease in the maximum valgus angle of the knee joint indicates that the knee has deviated from its valgus position [17]. When taekwondo shoes were worn, the smaller valgus angle compared with barefoot actions was likely because the outsole cushion on the taekwondo shoes absorbed the ground impact force when landing, and movement compensating for the impact force appeared to be small. Jo [18] reported that being barefoot resulted in a more flexible landing than when wearing shoes and that, when barefoot, the human body dissipates the ground reaction force by increasing the knee joint angle. Park [19] reported that during dance movements, dancing barefoot resulted in greater impact forces than when wearing dancing shoes, because of the shock-absorbing capacity of the dance shoe insole. Based on these two preceding studies, the reason our barefoot values showed a greater valgus angle than while wearing two types of taekwondo shoes was primarily because of a non-shock-absorbing mechanism, which involves the body's compensatory action to reduce the force applied to the knee through increasing the shock absorption time. Therefore, it is possible that the risk of damage to the anterior cruciate ligament is further reduced on the side of the maximum knee valgus angle when wearing taekwondo shoes as opposed to performing these actions while barefoot.

The maximum knee extension moment at landing has been reported to be one of the risk factors for anterior cruciate ligament injury [3,20]. Yu et al. [20] reported that when the knee extension moment is increased, the shear force that causes the tibia to slide forward is also increased. Minimizing the shearing force is important as the increase in the tibia's anterior thrust raises the possibility of anterior cruciate ligament injury. Hewett et al. [3] reported that an increase in the knee extension moment increases tension on the anterior cruciate ligament, thereby raising the risk of injury. In our study, no statistically significant difference was found in the maximum knee extension moment according to whether taekwondo shoes were worn during the jump whip kick actions; however, the numerical values for both models A and B were smaller than those obtained when performing

Table 1 Change in variables.

	Barefoot (a)	Model A (b)	Model B (c)	F	*P*	Post-hoc
Maximum hip flexion angle (degree)	28.64 ± 6.56	30.85 ± 10.30	32.99 ± 9.40	0.598	0.557	
Maximum knee valgus angle (degree)	13.94 ± 2.94	10.21 ± 2.66	10.18 ± 2.14	6.901	0.004	a–b: 0.013 c–a: 0.012
Maximum knee extension moment (Nm/kg·cm)	1.47 ± 0.15	1.33 ± 0.16	1.30 ± 0.17	2.813	0.078	
Maximum knee lateral rotation moment (Nm/kg·cm)	−1.05 ± 0.17	−0.93 ± 0.15	−0.98 ± 0.13	1.575	0.226	
Activity ratio of the quadriceps and hamstring (%MVIC)	72.64 ± 6.62	65.52 ± 8.77	61.16 ± 7.90	5.493	0.010	a–c: 0.011

barefoot. The extension moment value was calculated based on the ground reaction force value and the moment arm of the knee joint, and it had a high correlation with the impact force. Kaelin et al. [21] reported the effects of outsole shoe material on impact force during a drop landing motion. They noted that the impact force generated by the landing motion of the soft shoe outsole reduced by up to 18%. In contrast, our study findings showed no such differences.

The maximum knee lateral rotational moment on landing has been reported to be a risk factor for anterior cruciate ligament injury [22]. Berns et al. [22] reported that the risk of anterior cruciate ligament injury is further increased when the shear force that causes tibial thrust is transmitted and lateral rotation is applied to the knee joint. In particular, the lateral rotational moment generated in the knee joint is highly correlated with anterior cruciate ligament injury because considerable anterior cruciate ligament torsion occurs due to the axial torque when the foot and knee are fixed to the ground [3,23]. The jump whip kick is a rotational jump kick based on a vertical axis, and rotational inertia occurs in the ankle and knee joints after landing. Accordingly, the tendency of the knee joint to rotate outward was noteworthy in our participants, and we hypothesized that taekwondo shoes could be an index used to determine whether they were effective in controlling rotation. However, our study findings indicated no statistically significant difference in the maximum knee lateral rotational moment either when wearing taekwondo shoes or not during the jump whip kick action. Park and Lee [11] reported a significant difference while wearing taekwondo shoes in one part of the rotational traction during the taekwondo rotation kick motion. Based on previous studies, we considered that taekwondo shoes would affect rotation; however, our study findings did not support this proposition. We consider that the main reason why the maximum knee laterals rotational moments in this study did not show any significant difference was due to the varied characteristics of the kick applied in this experiment, and further research should be undertaken to assess the relevant factors more precisely.

The activity ratio of the quadriceps and hamstring muscles at landing has also been reported to be a risk factor for anterior cruciate ligament injury [23,24]. Boerboom et al. [24] proposed that as the quadriceps activity ratio increases, the hamstring muscles weaken and the probability of an anterior cruciate ligament injury increases. Moreover, anterior cruciate ligament injury is prevented when the quadriceps and hamstring muscles co-contract. The hamstring muscles function to control excessive movement of the tibia [25]. The lower the hamstring muscle activity, the higher the risk of injury as the hamstring muscles are the only muscles to support anterior cruciate ligament tension. Therefore, combined quadriceps and hamstring muscle action prevents excessive anterior tibial push motion, which can help prevent anterior cruciate ligament injury. In this study, a significant difference was found between quadriceps and hamstring muscle activity ratios when participants wore taekwondo shoes during the jump whip kick motion and when performing this action barefoot and while wearing model B shoes. Our findings suggest that anterior cruciate ligament injury can be better avoided in terms of this activity ratio when wearing model B shoes than when performing these actions barefoot. No significant difference was found between quadriceps and hamstring muscle activity ratios when the jump whip kick motion was performed barefoot and while wearing model A shoes. However, the quadriceps muscle activity ratio while barefoot was higher than that when wearing model A shoes. While wearing taekwondo shoes, the quadriceps and hamstring muscle activity ratio decreased, which indicated that the activities of the quadriceps were lowered. In this study, the barefoot EMG activity ratio was 72.64; while wearing model A shoes, the EMG activity ratio was 65.52; and while wearing model B shoes, the EMG activity ratio was 61.16. At all three levels, the quadriceps muscles were more active than the hamstring muscles. However, considering that model A shoes decreased this activity by approximately 7% compared to barefoot actions and that model B shoes decreased this activity by approximately 11% compared to barefoot actions, it was clear that quadriceps and hamstring muscle co-contraction improved when wearing taekwondo shoes. Taekwondo shoes appear to have reduced the activity of the quadriceps muscles more than when performing barefoot as taekwondo shoes absorb the impact force and lower ground reaction forces. Reeves et al. [26] compared and analyzed muscle activity using muscle taping and reported that a decrease in soleus muscle activity when taped was related to ground repulsion when landing after jumping. Therefore, when considering these previous findings and the results of this study, it could be concluded that the activity of the quadriceps muscles decreased due to lowering of the ground repulsion resulting from the shock absorption of the taekwondo shoe outsole. It would appear that internal forces on the taekwondo shoes decreased due to the shock-absorbing capacities of the shoes. In terms of the activity ratio, no statistically significant differences were found between actions performed barefoot and when wearing model A shoes and performing barefoot and wearing model B shoes. This may have been due to differences in cushion thickness and materials in the forefoot and hindfoot outsoles of the taekwondo shoes. In model B shoes, the hindfoot outsole material was softer with thicker cushioning than that of model A shoes, and model B shoes could better withstand impact forces.

5. Conclusion

Wearing taekwondo shoes had a positive effect on preventing anterior cruciate ligament injury; therefore, the importance of wearing taekwondo shoes should be clearly communicated to athletes and coaches to increase their frequency of use and change negative perceptions regarding taekwondo shoe use during training. Further studies are needed to confirm our results through experiments comprising tasks such as drop landing and vertical jumps that are more involving than the jump whip kick motion used in taekwondo competitions.

Disclosure of interest

The authors declare that they have no competing interest.

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