Motion analysis study of quick turning motions
- a possibility of the triggering hallux valgus -

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Abstract

Introduction: It has been noted that repetitive quick turning motions in sporting activities could be a cause of hallux valgus deformity. We have supposed that repetitions of hallux dorsiflexion and forefoot pronation during quick turning motions may contribute to the development of hallux valgus. We therefore evaluated forefoot motions experimentally during quick turning motions using motion analysis systems.

Methods: Nine normal adult volunteers performed shuttle side stepping across three white lines on the floor as a model of quick turning motions. The motion state from toe contact to toe off in turning during shuttle side-stepping was evaluated by photographs using a high-speed camera. To measure the ground reaction force during turning, a force plate was placed on the most lateral white line for the test foot. Three-dimensional angular variations of the first metatarsophalangeal (MTP) joint, the so-called spatial MTP angle, was measured using a three-dimensional motion analysis system equipped with six cameras.

Results: Photographs from the high-speed camera showed that shuttle side-stepping was comprised of toe contact (TC), turning direction (TD) and toe off (TO) phases. Using the camera, hallux dorsiflexion and forefoot pronation were observed in the TC and TO phases. The force plate detected an increase of the vertical component of the ground reaction force in the TC phase. The spatial MTP angle during shuttle side-stepping drastically decreased after toe contact, approaching the value in a standing posture, and drastically increased just before toe off.

Conclusion: These findings suggest that drastic variation of the spatial MTP angle and repetitions of forefoot pronation and hallux dorsiflexion under weight bearing may exert dynamic abduction stress on the first MTP joint. In conclusion, such increased abduction stress during repetitive quick turning motions may cause laxity of the medial collateral ligament in the first MTP joint, which has a possibility to develop into hallux valgus.

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Introduction

It has been known that hallux valgus deformity is caused by genetic, anatomical, and external factors,[1, 2] Berman[3] reported hallux valgus induced by dynamic sporting activity. He reported that this deformation may be caused by forefoot pronation under weight bearing, such as jumping and quick turning in the presence of joint laxity. In sports requiring frequent quick turns, forced forefoot pronation often occurs and has been considered to be one of the causes of hallux valgus[3]. Fabeck et al.[4] reported a case of traumatic rupture of the medial collateral ligament of the first metatarsophalangeal (MTP) joint of a soccer player, which developed into hallux valgus. However, there have been only a few studies[3,4] which experimentally evaluated motions possibly developing into hallux valgus or investigated the involvement of the medial collateral ligament of the first MTP joint in the development of hallux valgus. Therefore, by using motion analysis systems, we investigated foot motion in healthy normal volunteers during shuttle side-stepping, as a model of quick turning motion. On the basis of the results, we evaluated the effect of quick turning motions on the development of hallux valgus.

Methods

Subjects

The subjects were nine healthy adult volunteers (four males and five females, mean ± S.D., 21.4 ± 1.5 years old) without hallux valgus and with no history of trauma in the lower extremities. Of the subjects, two (a male and a female) were college students who belonged to a basketball club, and the other seven subjects had experience in various field sports, such as judo or karate, but no club activities at college. This study was approved by the local ethics committee and adhered to the Helsinki Declaration. All subjects gave informed consent.

A model of quick turning

The subjects performed shuttle side stepping across three lines drawn at 1.0 m intervals on the floor. A force plate (Force Plate System 9286A, Kistler Instrument, NY, USA) was placed on the most lateral white line for the test foot so that it could make contact with the plate (Fig. 1). Measurements of one foot were taken three times during three series of shuttle side stepping, and the mean values of the obtained data were calculated. Measurements were performed separately for the right and left feet. The force plate was moved when the test foot was changed from right to left. The shuttle side stepping was performed at maximum speed in each subject.

Measurement indices

The following indices of the test foot were measured during shuttle side stepping:

1) the motional state,
2) the ground reaction force,
3) the three-dimensional angular variations of the first MTP joint, the so-called spatial MTP angle.

1) Observation of motional state

During the measurement, photographs were taken at 500 frames / sec using a high-speed camera (FASTCAM Ultima40K, Photron Co. Ltd., Tokyo, Japan). The camera was installed 1.0 m above and 1.0 m in front of the force plate (Fig. 1).

2) Detection of ground reaction force

Detection apparatus for the ground reaction force and its location were mentioned above. The fore and aft, lateral and vertical components of the ground reaction force were defined as Force X, Force Y, and Force Z, respectively.

3) Measurement of the spatial MTP angle

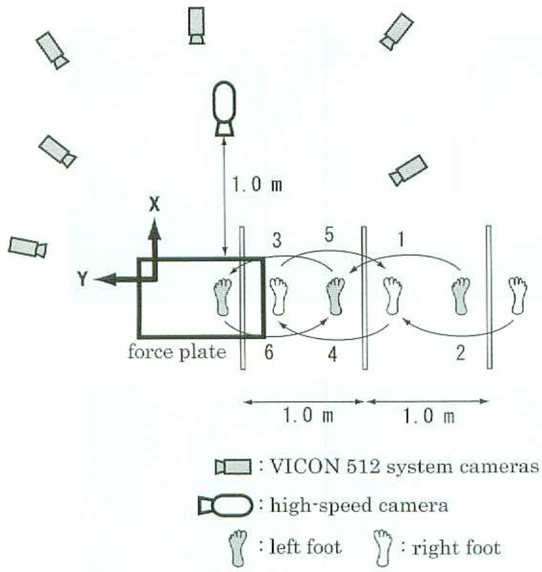

Fig. 1.

Schema of the manner of shuttle side stepping and the installation location of the experimental apparatus. Each subject performed shuttle side stepping across three white lines drawn at 1.0 m intervals. Each number indicates the stepping order. This schema shows the left foot as the test foot. A force plate was placed on the white line of the most lateral side for the test foot so that it could make contact with the plate at turning. A high-speed camera was installed 1.0 m above and 1.0 m in front of the force plate. Six cameras for three-dimensional motion analysis were installed in front of the subject.

The spatial MTP angle was measured using a three-dimensional motion analysis system (VICON 512 system, Vicon Motions Systems Inc., CA, USA) including six 60 Hz cameras installed in front of the subjects (Fig. 1). Three spherical reflective markers (14.5 mm in diameter) were attached with double-sided adhesive tape to the following sites immediately above: A) the head of the first phalanx, B) the head of the first metatarsal and C) the base of the first metatarsal. We defined the spatial MTP angle as the acute angle between lines A-B and B-C, as shown in Fig.2. The spatial MTP angle in a standing position was measured first, and then the variation of the angle during shuttle side stepping was measured.

Results

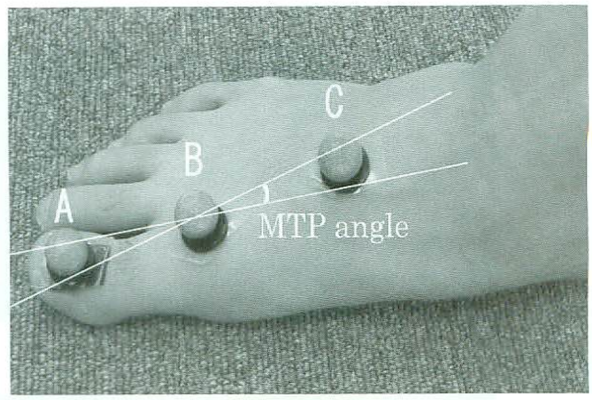

Fig. 2.

Schema of the three-dimensional angle of the first metatarsophalangeal joint (the so-called the spatial MTP angle). Three spherical reflective markers were attached with double sided adhesive tape to the following sites: A) the root of the nail and B) the head of the first metatarsal and C) the base of the first metatarsal. The spatial MTP angle was defined as the acute angle between lines A-B and B-C. The spatial MTP angle was measured and analyzed by a three-dimensional motion analysis system equipped with six cameras.

The motional state during shuttle side stepping

It is generally known that gait commences with heel contact and terminates with toe off (TO)[5]. In this experiment, however, photographs from the high-speed camera showed that the shuttle side stepping started from the toe contact (TC) phase and terminated with the TO phase, as shown in Fig. 3. Both phases were determined by photographs from a high-speed camera in combination with Force Z of the ground reaction force. The intermediate period of both phases was called the "turning of direction" (TD) phase. Figs 3-1-a and 3-2-a showed that the TC phase started from the contact of the anteromedial side of the first MTP joint and the first metatarsal. The subsequent TD phase showed different patterns among the subjects. The heel contact position was the medial side to the forefoot contact position in the two subjects with basketball experience (Fig. 3-1-c), but collinear to (two subjects) or lateral to (five subjects, Fig. 3-2-c) the forefoot contact position in the other seven

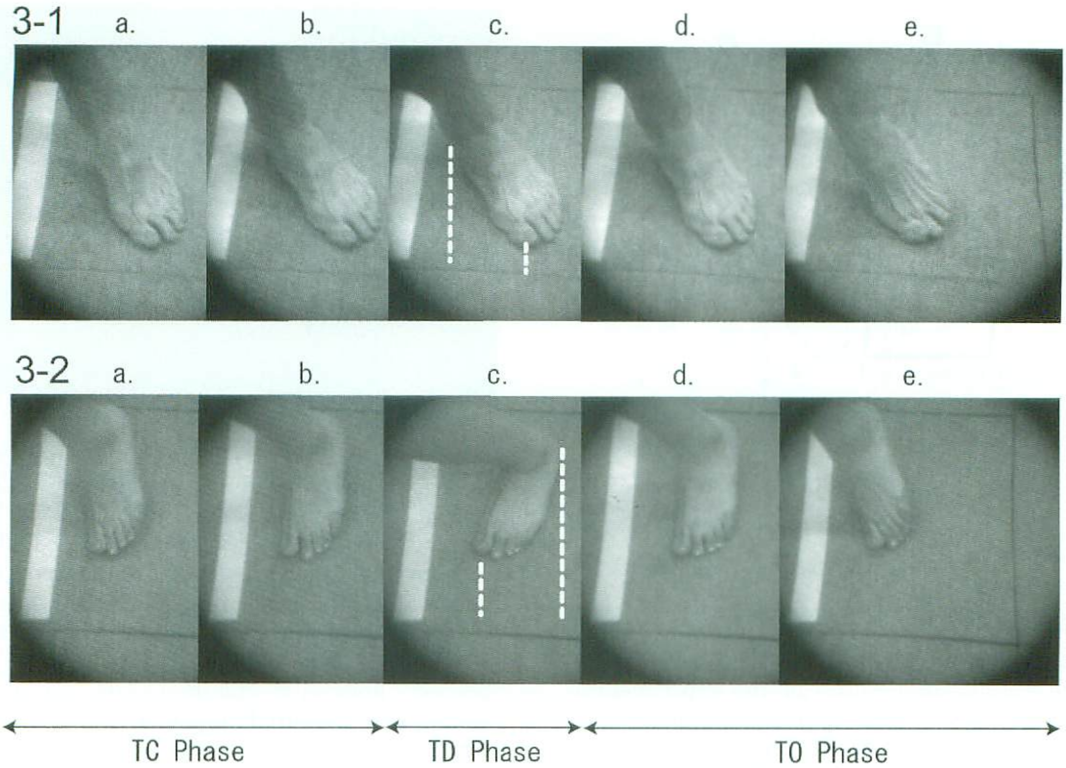

Fig. 3.

The photographs during turning motion across the most lateral white line on the floor. 3-1: a series of photographs shows the turning motion of a representative subject in whom the heel contact position was medial for the toe contact position. 3-2: a series of photographs shows the turning motion of a representative subject in whom the heel contact position was lateral for the toe contact position. The photographs show the motion in the toe contact (TC) phase (a & b), in the turning of direction (TD) phase (c) and in the toe off (TO) phase (d & e). Each phase was determined from photographs using a high-speed camera in combination with Force Z of ground reaction force. The photographs were taken at 500 frames/sec.

subjects. The TO phase started from the takeoff of the heel and terminated at the takeoff of the antero-medial side of the first MTP joint and first metatarsal, as shown in Figs. 3-1-d, 3-1-e, 3-2-d and 3-2-e.

Characteristic features were revealed in the two subjects with basketball experience, which requires quick turning motions. As shown in Fig. 3-1, in those subjects, hallux dorsiflexion and forefoot pronation were continually observed in all phases. On the other hand, in the other seven subjects, dorsiflexion and pronation were observed only in the TC and TO phases because a period of foot flat existed during the TD phase, as shown in Fig. 3-2.

Ground reaction force

At toe contact, Forces Y and Z of the ground reaction force increased and gently decreased in all subjects. In the early TO phase, Forces Y and Z increased again in seven subjects, including the two subjects with basketball experience (Fig. 4-1) but did not in the others (Fig. 4-2). In the normalized data using the body weight of each subject, the peak values (mean $\pm$ SE) of Force Y/body weight and Force Z/body weight were 84.1 $\pm$ 3.0%, and 162.4 $\pm$ 7.2% after toe contact, respectively. In Force X, no characteristic variations occurred (n=9).

Variations of the spatial MTP angle

Fig. 5 shows each variation of the spatial MTP angles in a standing position and during the shuttle side stepping. The angle drastically decreased after toe contact, approaching the value in a standing position, and drastically increased just before toe off. This pattern occurred in all subjects, but three different patterns were observed in the TD phase. In the two subjects with basketball experience, the spatial MTP angle in the early TD phase was almost identical to that in a standing position, but then slightly increased, as shown in Fig. 5-1. In the middle and late TD phases, the value remained at a slightly higher level compared

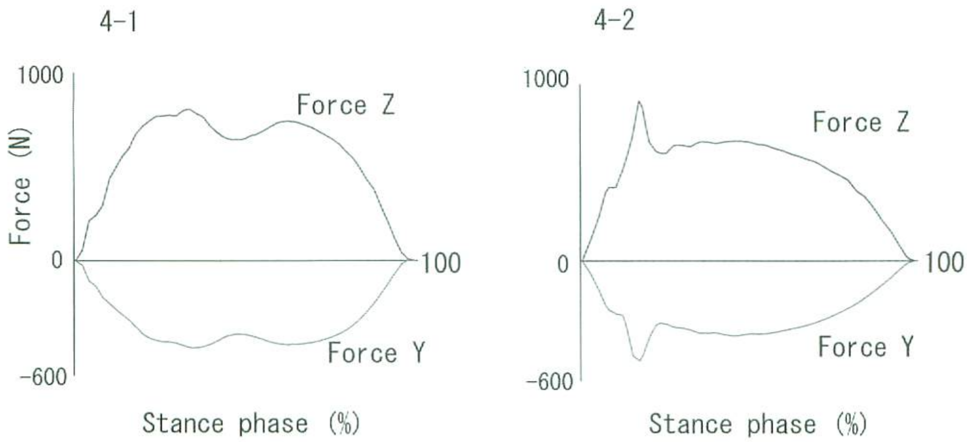

Fig. 4.

Forces Y and Z of ground reaction force during shuttle side stepping. In all subjects, Forces Y and Z of the ground reaction force increased at toe contact. However, two different patterns were found in the early TO phase. 4-1: a representative graph in seven subjects including two subjects with basketball experience shows moderate increase in the early TO phase. 4-2: a representative graph in the other two subjects shows gradual decrease in the early TO phase.

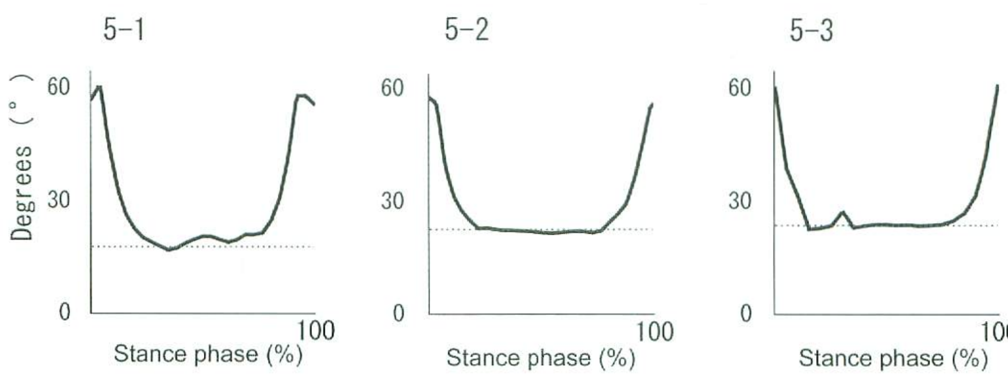

Fig. 5.

Variations of the spatial MTP angle in a standing position (dotted line) and during shuttle side stepping (bold solid line). Three different patterns were found, consistent with the three patterns of the different relative positions between heel contact and toe contact. 5-1: This shows representative data in two subjects with basketball experience in whom the heel contact position was medial for the toe contact position. 5-2: This shows representative data in two subjects in whom the heel contact position was collinear with the forefoot contact position. 5-3: This shows representative data in five subjects in whom the heel contact position was lateral for the forefoot contact position.

with that in a standing position, as shown in Fig. 5-1. In the other seven subjects, the spatial MTP angle in the early TD phase was also almost identical to that in a standing position. In the middle and late TD phases, however, two patterns were shown in respect to variations of the spatial MTP angle. In two subjects in whom the heel contact position was collinear with the fore-foot contact position, the angle remained almost identical compared with that in a standing position, as shown in Fig. 5-2. In five subjects in whom the heel contact posi-tion was lateral to the forefoot contact posi-tion, the angle showed a transient increase, followed by variations at almost the same level compared with the standing position, as shown in Fig. 5-3.

In all indices in this study, no remarkable difference was observed between the right and left feet in all subjects.

Discussion

Hallux valgus is characterized by valgus deformity of the first proximal phalanx and varus deformity of the first metatarsal, and the latter has been considered to precede the former[6]. Several researchers have pointed out that abductor-adductor muscle imbalance may be a major factor in the development of hallux valgus[7,8]. In patients with hallux valgus, the adductor force of the adductor hallucis muscle is markedly decreased, whereas the abductor hallucis muscle loses the abductor force completely[9]. Therefore, in the patient, the hallux pronates and the abductor hallucis muscle moves to the plantar side and the adductor hallucis muscle moves to the lateral side[10]. As one of the causes of muscle imbalance, laxity or rupture of the medial collateral ligament has been considered[4].

According to that theory, we considered that the laxity of the medial collateral ligament may be closely associated with the development of hallux valgus caused by quick turning motions. Furthermore, we have supposed that repetitions of hallux dorsiflexion and forefoot pronation during quick turning motions may contribute to the development of laxity of the medial collateral ligament. Therefore, it was necessary to demonstrate the occurrence of hallux dorsiflexion and forefoot pronation during quick turning motions. Using shuttle side stepping, we experimentally reproduced quick turning motions in sporting activity. Acute turnings of direction are forced in shuttle side stepping, which resembles quick turning motions. However, changes of direction in quick turning motions are multi-way in sporting activity, but turns in shuttle side stepping are only one way. Qualitative analysis of acute turning in one direction should be performed initially. Therefore, we considered that shuttle side stepping was an appropriate model to investigate the relationship between the development of hallux valgus and repeated hallux dorsiflexion and forefoot pronation under weight bearing.

In this study, in all subjects, hallux dorsiflexion and forefoot pronation were observed in the TC phase by a high-speed camera. Additionally, Forces Y and Z of the ground reaction force increased in the TC phase. An increase of Force Y indicates suppression of the force toward the lateral side while that of Force Z indicates weight bearing. Perry[5] showed that each peak value of Forces Y and Z of the ground reaction force in gait was approximately 3% and 110% of the body weight, respectively. In this study, both values of Forces Y and Z in shuttle side stepping were remarkably higher than those in gait. Thus, in the TC phase, the forefoot was in pronation and received a high load vertically and horizontally, and the hallux was forced dorsiflexion. In the early TO phase, Forces Y and Z increased again in seven subjects, including the two subjects with basketball experience (Fig. 5-1), but not in other subjects (Fig. 5-2). These different patterns may have originated for the following reasons: the former subjects took off mainly using the test foot, which was lateral to the white line on the floor (Fig. 5-1), while the latter subjects took off mainly using the other foot, which was medial to the white line on the floor (Fig. 5-2). In the former subjects, these results indicated that weight bearing occurred on the test foot in the TO phase. Additionally, in the former subjects, three experimental indices indicated that hallux dorsiflexion and forefoot pronation in the test foot under weight bearing occurred, in all three phases of two subjects with basketball experiences, and in the TC and TO phases of the other five subjects. In the latter subjects, the indices indicated that dorsiflexion and pronation in the test foot under weight bearing occurred in only the TC phase. In relation to the state of the hallux and the load on the forefoot, it is known that wearing high heels promotes weight bearing on the forefoot and forces hallux dorsiflexion[11]. Shimizu et al.[11] pointed out that those states may induce abduction stress on the first MTP joint. Furthermore, they concluded that this stress may be one of the causes of hallux valgus[11]. Thus, it has been indicated that relative moderate continuous abduction stress may develop hallux valgus. Therefore, in this study, we noted that hallux dorsiflexion and forefoot pronation under weight bearing during shuttle side stepping may induce dynamic abduction stress on the first MTP joint, suggesting that the stress might be related to the development of hallux valgus.

In the TD phase, in subjects in whom the heel contact position was lateral to the forefoot contact position, the spatial MTP angle showed a slight and transient increase in the early TD phase. The spatial MTP angle reflects hallux dorsiflexion and abduction. From the photographs indicating the foot flat stage (Fig. 3-2-c) and the transient increase of the spatial MTP angle in the TD phase (Fig. 5-3), it is considered that abduction stress may be induced in the first MTP joint also in the TD phase in such subjects. On the other hand, in subjects with basketball experience, the foot flat stage hardly existed and the spatial MTP angle was almost steady state in the TD phase (Fig, 5-1). Therefore, this suggests that basketball players may minimize the duration of contact of the entire planta by moving as quickly as possible and performing quick turns mainly using the forefoot.

As mentioned above, during shuttle side stepping, hallux dorsiflexion and forefoot pronation were repeated, especially in the subjects in whom the heel contact position was lateral to the forefoot contact position. Therefore, a stretching load on the first medial collateral ligament may be forced in such subjects. In light of our findings, we can propose a hypothesis of the stretching load as follows: 1) in the TC phase, the hallux is in dorsiflexion, and laxity of the medial collateral ligament may induce abduction instability in the first MTP joint. 2) In the TD phase, the dorsiflexion position of the hallux is drastically changed to the intermediate position. Therefore, the medial collateral ligament may be immediately tensed. 3) Simultaneously, the heel contact lateral to the forefoot may exert an acute stretching load on the medial collateral ligament. From these serial motions, the medial collateral ligament may be immediately changed from laxity to tension. Thus, repetitive quick turning motions in sporting activities may cause minor injuries in the first medial collateral ligament. It is known that the ligament is injured not only by great, but also by slight external force, depending on the speed and frequency of the force. The ligament is viscoelastic and is characterized by the creep phenomenon that induces irreversible changes[12]. Therefore, we could speculate that repeated external force in sporting activities may also cause laxity of the medial collateral ligament in the first MTP joint, which has a possibility to develop into hallux valgus.

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カッティング動作の動作解析
－外反母趾の一誘因としての可能性に関する検討－

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要旨：スポーツ時のカッティング動作の繰り返しにより，前足部は回内位での荷重負荷を強制されることが多く，このことがスポーツ傷害としての外反母趾の成因の一つとされている．しかしながらこの動作と外反母趾の関係を実験的に示した報告はない．そこで今回われわれはカッティング動作の実験的モデルとして被験者に反復横跳びを行わせ，方向転換時の前足部の状態を，動作解析システムを用いて測定・解析した．被験者は，外反母趾がなく現在までに重篤な下肢の外傷の既往がない健常成人９名（19～24歳，平均年齢21.4歳）とした．実験的モデルとしての反復横跳び動作は，１m間隔の３本のラインを跨ぐように行わせた．測定は，反復横跳び方向転換時の着地から離地までの状態を，ハイスピードカメラ，床反力計，３次元動作解析システムを用いて行った．ハイスピードカメラにより可視画像を撮像し，床反力計により床反力の各成分を，３次元動作解析システムにより母趾中足趾節関節（母趾MTP関節）の外反空間角度（MTP角）の変化を測定・解析した．その結果，ハイスピードカメラでは，着地および離地時に前足部の回内が認められた．床反力は，着地時ではすべての被検者において，また，離地時は２名を除いて鉛直成分が増大した．これらのことから，着地時および離地時では，前足部は回内位での荷重負荷状態であることが示された．一方，３次元動作解析システムにより，母趾MTP関節は着地時から離地時にかけて背屈位から中間位，そして背屈位への推移がみられ，また，足底接地期においては，母趾MTP関節の外反角度の増大を示す被験者もみられた．これらの結果から，カッティング動作のモデルとしての反復横跳びにおいて，母趾MTP関節の側副靭帯が急激な弛緩，緊張を繰り返すことが示唆された．このことと，靭帯の粘弾性体という性質を併せて考えると，カッティング動作の高頻度の繰り返しによって，側副靭帯そのものが徐々に弛緩する可能性が考えられた．また，母趾MTP関節の側副靭帯の断裂あるいは靭帯自体の弛緩が外反母趾の成因であるとの報告があり，これらの報告と実験結果から，カッティング動作の高頻度の繰り返しが外反母趾変形の成因に成りえることが示唆された．

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