65 The Art of the Musculoskeletal Physical Exam: Foot and Toes Biomechanics of the Foot

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65.1 Terminology of the Motion

The terminology to describe the motion of the foot and ankle contains a number of ambiguities [1, 2]. The American Academy of Orthopaedic Surgeons (AAOS) [3], Kapandji [4], the American Orthopaedic Foot and Ankle Society (AOFAS) [5], and the International Society of Biomechanics (ISB) [6] use different terms to describe the same movement to use the three planes, transverse (horizontal), sagittal, and frontal (coronal), to express the joint motions (Table 65.1). About the terms of inversion/eversion and supination/pronation, there are two opinions. One is the concept defining inversion/eversion as coronal plane motion and supination/pronation as triplane motion, advocated by the AOFAS and the ISB. The other is the concept defining inversion/eversion as triplane motion and supination/pronation as coronal plane motion, advocated by Kapandji and the AAOS. In sagittal plane, it was defined as extension/flexion (dorsiflexion/plantar flexion) in the terminology of the AAOS; however, extension/flexion is defined as the reverse motion by Kapandji.

The Ad Hoc Committee of Terminology of the Japanese Society for Surgery of the Foot (JSSF) reviewed previous articles describing the transverse (horizontal) plane, sagittal plane, and frontal (coronal) plane motions of the hindfoot, midfoot, and forefoot (Fig. 65.1) [7]. According to the terminology utilized in a total of 160 literatures being explored by examining related academic papers retrieved through a search of the PubMed medical literature database (www.pubmed.com) up to 2008, the Ad Hoc Committee of Terminology of the JSSF proposed for the foot/ankle motion as follows (Table 65.2) [8]: abduction/adduction comprises motion of the ankle joint, subtalar joint, and Chopart/Lisfranc joint in the transverse (horizontal) plane (Fig. 65.2); dorsiflexion/plantar flexion comprises motion of the ankle joint, subtalar joint, and Chopart/Lisfranc joint in the sagittal plane (Fig. 65.3); and inversion/eversion comprises motion of the ankle joint, subtalar joint, and Chopart/Lisfranc joint in the frontal (coronal) plane (Fig. 65.4). Supination/pronation is a complex joint motion in the triplane. Pronation is the complex motion of dorsiflexion, abduction, and eversion comprised of motion of the ankle joint, subtalar joint, and Chopart/Lisfranc joint (Fig. 65.5, left). Supination is the complex motion of plantar flexion, adduction, and inversion comprised of motion of the ankle joint, subtalar joint, and Chopart/Lisfranc joint (Fig. 65.5, right). Proposed terminology for joint motion of toes is as follows: abduction/adduction is composed of the motion of MTP joint, IP joint of great toe, and PIP and DIP joints of toes in transverse (horizontal) plane; extension/

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Table 65.1 Definition of joint motion of foot and ankle by the AAOS, Kapandji, AOFAS, and ISB

Plane	AAOS [3]	Kapandji [4]	AOFAS [5]	ISB [6]
Transvers (horizontal)	Abduction Adduction	Abduction Adduction	Forefoot/midfoot Abduction Abduction Ankle/hindfoot External rotation Internal rotation	Forefoot/midfoot External rotation Internal rotation Ankle/hindfoot External rotation Internal rotation
Sagittal	Extension (dorsiflexion) Flexion (Planatarflexion)	Flexion Extension	Dorsiflexion Plantarflexion	Dorsiflexion Plantarflexion
Frontal (coronal)	Forefoot Pronation Supination Hindfoot Eversion Inversion	Forefoot Pronation Supination Hindfoot Eversion Inversion	Eversion Inversion	Eversion Inversion

AAOS the American Academy of Orthopaedic Surgeons, *AOFAS* the American Orthopaedic Foot and Ankle Society, *ISB* the International Society of Biomechanics

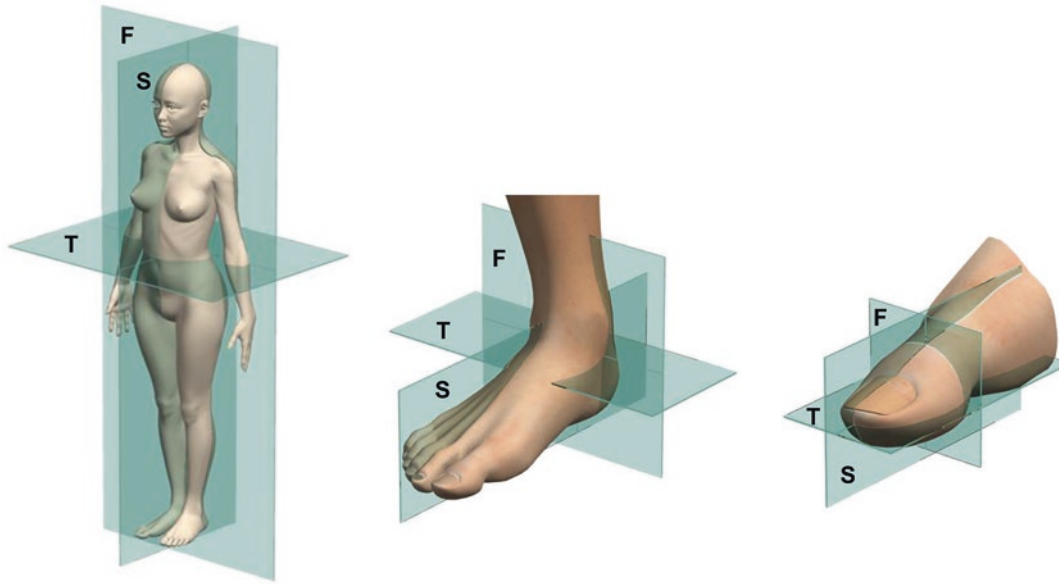

Fig. 65.1 Triplane of the whole body (left), hindfoot and midfoot (center), and forefoot (right)**.** *T* transverse (horizontal) plane, *S* sagittal plane, *F* frontal (coronal). Reproduced from "Terminology of Foot & Ankle Surgery" with permission from the Glossary of the Japanese Society of Foot Surgery

flexion is composed of the motion of MTP joint, IP joint of great toe, and PIP and DIP joints of toes in sagittal plane; and supination/pronation is composed of the motion of MTP joint, IP joint of great toe, and PIP and DIP joints of toes in frontal (coronal) plane.

Although there still remains terminological chaos to describe the motion of the foot and ankle, it is considered that the proposed terminology described by the Ad Hoc Committee of Terminology of the JSSF reflects the opinion of majority.

Table 65.2 Definition of joint motion of foot and ankle proposed by the Ad Hoc Committee of Terminology of the Japanese Society for Surgery of the Foot

Plane	Foot and ankle	Toe (MTP/PIP/DIP)
Transverse (horizontal)	Abduction Adduction	Abduction Adduction
Sagittal	Dorsiflexion Plantarflexion	Extension Flexion
Frontal (coronal)	Eversion Inversion	Pronation Supination
Three planes (complex motion in triplane)	Pronation (Abduction in transvers plane Dorsiflexion in sagittal plane Eversion in frontal plane) Supination (Adduction in transvers plane plantarflexion in sagittal plane Inversion in frontal plane)	–

Fig. 65.2 Abduction (left) and adduction (right) of the hindfoot and midfoot in transverse (horizontal) plane

Fig. 65.3 Dorsiflexion (left) and plantar flexion (right) of the hindfoot and midfoot in sagittal plane

Fig. 65.4 Eversion (left) and inversion (right) of the hindfoot and midfoot in frontal (coronal) plane

Fig. 65.5 Pronation (left) and supination (right) of the hindfoot and midfoot in triplane. Pronation: dorsiflexion in sagittal plane, abduction in transverse (horizontal) plane, eversion in frontal (coronal) plane. Supination: plantar flexion in sagittal plane, adduction in transverse (horizontal) plane, inversion in frontal (coronal) plane

65.2 Biomechanics of the Foot

65.2.1 Functional Anatomy of Subtalar Joint

Subtalar joint has three functional axes and moves three-dimensionally [9]. Although the direction of the functional axis of the subtalar joint and the normal range of motion vary depending on the literature, it basically moves in plantar flexion, dorsiflexion, inversion, eversion, supination, and pronation. The subtalar joint is connected by the interosseous talocalcaneal ligament and the cervical ligament. These are called the subtalar cruciate ligaments, and the medial fibers of the cervical ligament in the tarsal canal contribute to "swing motion" of the subtalar joint [10].

A characteristic motion of the subtalar joint is supination and pronation. Most of the movement of the foot in the supination/pronation depends on the subtalar joint with the range of motion as 30–50° (25–30° of supination, 5–20° of pronation). Therefore, in patients with talocalcaneal coalition (Fig. 65.6, left) or severe posterior ankle impingement syndrome, it is difficult to take a position of the supination of the foot due to limited movement of the subtalar joint (Fig. 65.6, right). During surgery, it is possible to know that a sufficient resection has been performed by confirming that the foot can take a normal supination position after excision of the lesion.

65.2.2 Functional Anatomy of Midfoot

The midfoot consists of the Chopart joint and the Lisfranc joint. Chopart joint consists of the calcaneocuboid joint and the talonavicular joint. Lisfranc joint consists of the metatarsocuneiform joint and the metatarsocuboid joint. The joint is moved by the bone being pulled by the tendon, and the movement is characterized by three factors: the distance between the axis of the motion and the tendon, the tendon's traction force, and the position where the tendon runs. Among them, the running position of the tendon is an important factor when considering the functional anatomy of the joint. The moment of tendon force with a short distance from the action axis is small, and the moment of tendon force with a long distance from the action axis is large. Figure 65.7 shows the motion axes of the midfoot. The tibialis pos-

Fig. 65.6 Patient with talocalcaneal coalition. Left: Lateral X-ray showed a coalition of subtalar joint (arrow). Right: Supination in right hindfoot is restricted relative to left side

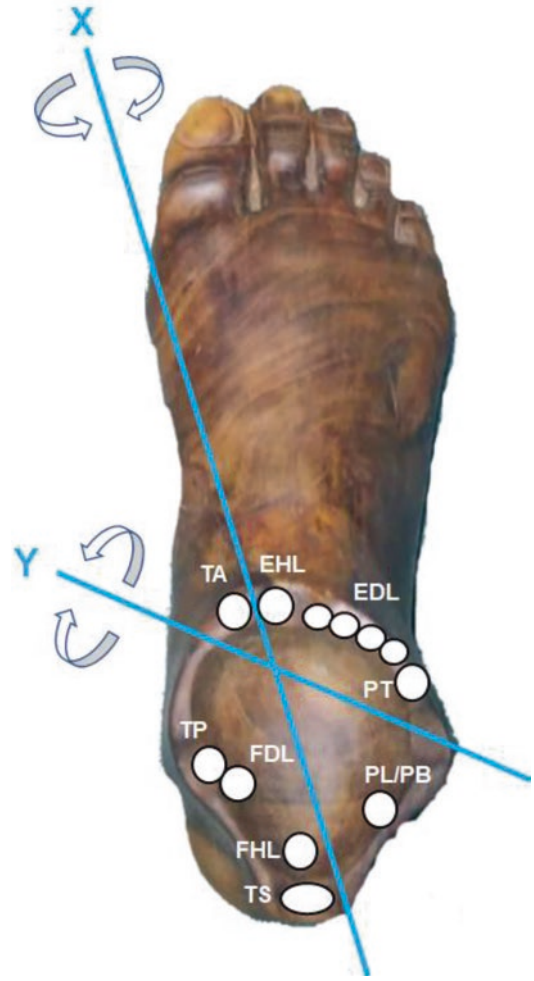

Fig. 65.7 Motion axes of the midfoot. *TA* tibialis anterior tendon, *EHL* extensor hallucis longus tendon, *EDL* extensor digitorum longus tendon, *PT* peroneus tertius tendon, *PL/PB* peroneus longus and brevis tendons, *TS* triceps surae (Achilles) tendon, *FHL* flexor hallucis longus tendon, *FDL* flexor digitorum longus tendon, *TP* tibialis posterior tendon

terior tendon and the flexor digitorum longus tendon running inward from X-axis contribute to the inversion, and the peroneus tendons located on the outside contribute to the eversion. At the same time, in standing position when the sole is in contact with the ground, the evertors rotate the lower leg internally, and the inverters rotate the lower leg externally. Dorsiflexion is performed by the traction force of the tibialis anterior tendon, the extensor hallucis longus tendon, and the extensor digitorum longus tendon. The plantar flexion is performed by the traction force of the Achilles tendon, the flexor hallucis longus tendon, and the flexor digitorum longus tendon.

The flexor hallucis longus and the flexor digitorum longus tendons not only are a source of toe movement in their anatomical attachment, but also contribute to the stabilization of each joint of the foot by coordinating with the plantar aponeurosis. In the toe-off phase, the toes stabilize each joint of the foot by tensioning the plantar aponeurosis while grasping the ground. At the same time, they act as a plantar flexor force of the ankle joint and the inversion force of the subtalar joint. On the other hand, the extensor hallucis longus and the extensor digitorum longus tendons act as the dorsiflexor force of the ankle joint and the eversion force of the subtalar joint during the period from the heel-strike to the foot-flat phase.

The Lisfranc ligament is the strongest ligament in the Lisfranc joint [11, 12] and plays an important role in the formation of the longitudinal arch of the foot and the stiffness of the foot during the toe-off phase [13].

65.2.3 Functional Anatomy of Forefoot

The long axis of each metatarsal is inclined with respect to the horizontal plane (Table 65.3), and disturbing this angle is considered to be the major cause of metatarsal pain [14]. The MTP joint has a larger range of motion in the dorsal direction and cooperates with the metatarsal and the IP joint [15, 16]. In the first stage of the toe-off phase in walking, the axis of motion of the forefoot passes between the second toes at an average angle of about 62° with respect to the line connecting the heads of the second and fifth metatarsals. In the next stage, the axis of motion moves to the first and second metatarsal heads [17].

Table 65.3 Angle of the inclination of each metatarsal with respect to horizontal plane

Metatarsal	Angle
1st	18–25°
2nd	15°
3rd	10°
4th	8°
5th	5°

65.2.4 Functional Anatomy of Toe

65.2.4.1 Hallux

Under non-weight-bearing, the IP joint of hallux exhibits a slightly dorsiflexion position due to the traction force of the extensor hallucis longus tendon. The extensor hallucis longus tendon runs through the center of the MTP and IP joints. In the hallux valgus, the extensor hallucis longus tendon is displaced laterally, so that it acts as an adductor for the hallux. As a result, the first metatarsal head is pushed medially, and the first metatarsal becomes inversion (Fig. 65.8).

The flexion of the MTP joint is carried out by the medial and lateral head of the flexor hallucis brevis, the adductor hallucis, and the abductor hallucis. The flexion force of the MTP joint is greater than the extension force due to the role of the sesamoid bone. Sesamoid bone has the function of increasing the bending moment of the intrinsic muscle by moving the plantar intrinsic muscle away from the motion axis of the MTP joint. Although resection of one side of sesamoid bone is usually not expected to cause significant problems, resection of both sides of sesamoid bones reduces the bending moment described above and reduces the flexion force required for MTP joints. In addition, since the sesamoid bone prevents the hyperextension of the IP joint in foot-flat phase, resection of both sides of sesamoid bones causes cock-up deformity of the IP joint.

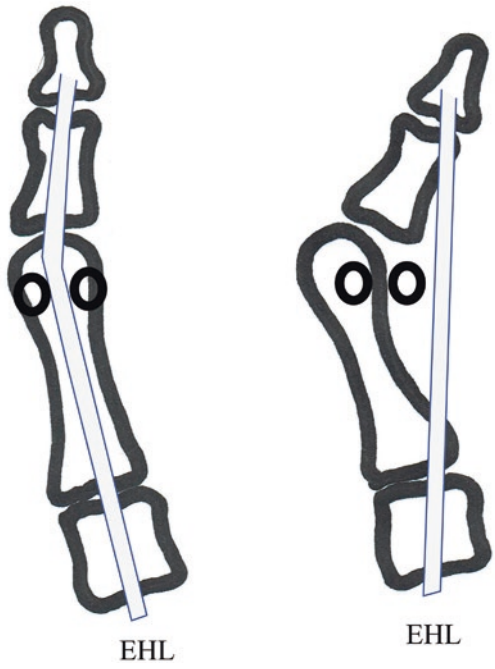

Fig. 65.8 Hallux valgus deformity and extensor hallucis longus tendon (EHL)
Right: normal. Left: hallux valgus

Table 65.4 The lesser toes' functional unit

Structures	Affected toes
The long extensors with the extensor digitorium brevis	2nd–4th toes
The flexor digitorum longus with the flexor digitorum brevis	2nd–5th toes
The planatar interosssei	3rd–5th toes
The dorsal interossei	2nd–4th toes
The lumbricals	2nd–5th toes
The abductor and the flexor digiti quinti	5th toe
The deep sagittal band attachment of the plantar aponeurosis	Proximal phalanx and the plantar plate of 2nd–5th toes

65.2.4.2 Lesser Toes

The lesser toes' functional units are divided into six (Table 65.4). All tendons passing to the axes of motion act as extensors, and all tendons passing plantar to the axes of motion act as flexors. At the MTP joint level, the dorsal and plantar interosseous tendon and the lumbrical tendon pass on the plantar side relative to the axis of motion and contribute to the flexion of the MTP joint. Distal to the MTP joint, lumbrical tendon and a part of interosseous tendon pass dorsally with respect to the axis of motion of the PIP joint, acting as extensor tendons.

The long extensors and the extensor digitorum brevis are strongly attached to the plantar aspect of the proximal phalanx through the transverse portion of the extensor aponeurotic lamina. They have only a loose connection with the dorsal capsule or the dorsum of the proximal phalanx. A pull applied on the long extensor tendon results in a hyperextension of the proximal phalanx at the MTP joint [18, 19]. The proximal phalanx is lifted into extension through the dorsal pull exerted by the proximal transverse segment of the dorsal extensor apparatus as the sling mechanism of extension. The proximal phalanx is extended, but the middle and distal phalanges remain slightly flexed.

The plantar aponeurosis, interosseous tendon, and lumbrical tendon are responsible for flexion of the MTP joint. When the plantar aponeurosis relaxes as in the case of the pronation foot, or when the interosseous muscle and the lumbrical muscle atrophy, the flexion force of the MTP joint decreases and the MTP joint is in the extended position. At that time, tension is applied to the long flexor tendon at the plantar of the MTP joint, so that the PIP/DIP joint will be in flexion, resulting in a hammertoe.

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