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Review article

Review of ankle inversion sprain simulators in the biomechanics laboratory

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Abstract

Ankle inversion ligamentous sprain is one of the most common sports injuries. The most direct way is to investigate real injury incidents, but it is unethical and impossible to replicate on test participants. Simulators including tilt platforms, trapdoors, and fulcrum devices were designed to mimic ankle inversion movements in laboratories. Inversion angle was the only element considered in early designs; however, an ankle sprain is composed of inversion and plantarflexion in clinical observations. Inversion velocity is another parameter that increased the reality of simulation. This review summarised the simulators, and aimed to compare and contrast their features and settings.

Keywords: ankle biomechanics; ankle injuries; inversion; sprain simulation

Introduction

Ankle inversion ligamentous sprain is very common in sports. It accounts for > 80% of all ankle injuries, and the recurrence rate is as high as 80%.[1] Individuals having recurrent ankle sprains are highly susceptible to chronic ankle instability and stiffness.[2] Extensive clinical and basic science research on this injury has been conducted.[3−5] The ankle complex consists of three articulations: the talocrural joint, the subtalar joint, and the distal tibiofibular syndesmosis. These joints allow the rearfoot to move as a single unit in multiplanes rather than in one single plane.[6] Most of the ankle injuries take place during jump landing[7] when the foot is inverted and plantarflexed,[8] also known as supination.[9]

Excessive supination can damage the lateral ligament complex structure. Three main ligaments are found in this complex: the anterior talofibular ligament, the posterior talofibular ligament, and the calcaneofibular ligament. Among these three ligaments, the anterior talofibular ligament is most vulnerable because it bears the greatest strain when the foot undergoes plantarflexion.[10] It has the lowest ultimate load of 138.9 N,[11] which makes it the first ligament to be injured in inversion sprain cases.[12]

Various approaches were reported in the literature to understand the injury mechanism quantitatively. The biomechanics of ankle supination sprain was first evaluated in cadaver studies.[13−15] The computational forward dynamic method was performed to determine the influence of foot position at touchdown on ankle sprain susceptibility by simulating side-shuffle movement kinematics.[16] Injuries were captured by calibrated motion analysis equipment in biomechanics laboratories occasionally. Three injury case reports with kinematics data have been published recently.[17−19]

The most direct way to study injury mechanism is to investigate real incidents; however, it is impossible and unethical to perform experiments that are intentionally hurting the test participants. To study ankle inversion sprain movements in calibrated environment, subinjury trials could be carried out with the assistance of tilt platforms, trapdoors, and fulcrum

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devices. This review provides information on the existing ankle inversion simulators. In addition, it compares and contrasts their features in terms of their inversion angles, inversion velocities, supination angles, and appearance (see Table 1).

Materials and methods

A systematic search of AMED, Embase (via OvidSP), MEDLINE, and SPORTDiscus was conducted from the earliest archives to the last week of December 2013. The keyword string used for search was "ankle AND (inversion sprain* OR inversion injur* OR sprain* OR strain* OR instabilit* OR ankle instabilit* OR chronic instabilit* OR joint instabilit* OR mechanical instabilit* OR functional instabilit* OR perceived instabilit* OR subjective instabilit* OR unstab* OR lax* OR giv* way) AND (sudden fall OR standing ankle inversion OR perturbation OR supinati* platform OR tilt* platform OR simulati* inversion OR simulati* platform OR fulcrum) AND (lab* OR biomechanic* lab*)", which appeared in the title, abstract, or keyword fields. The initial total number of articles in the database was 259. Results were first screened by reading the title and abstract. Nonrelevant articles were eliminated and the count was reduced to 80. Reference lists of the selected published journals were screened to retrieve additional studies. Duplicates, non-English articles, animal studies, and nonrelevant reports were excluded. Full texts of articles were obtained from the university library system. Data related to inversion angle, inversion velocity, supination angle, and appearance of the instrument were extracted. After the screening process, the final number of articles included in this review was 46.

Table 1
Categorisations of trapdoors, tilt platforms, and fulcrum devices.

Appearance	Reference
Trapdoor or tilt platform	Sprigings et al[20]
	Nawoczenski et al[21]
	Johnson & Johnson[22]
	Lynch et al[23]
	Podzielny & Hennig[24]
	Vaes et al[25,26]
	Anderson et al[32]
	Chan et al[34]
	Cordova et al[35]
	Cordova & Ingersoll[36]
	Ebig et al[37]
	Eechaute et al[38]
	Eechaute et al[39]
	Eils & Rosenbaum[40]
	Grüneberg et al[41]
	Isakov et al[43]
	Karlsson & Andreasson[44]
	Kimura et al[45]
	Konradsen & Ravn[46]
	Konradsen et al[47]
	Lofvenberg et al[48]
	Lohrer et al[49]
	Myers et al[50]
	Nieuwenhuijzen et al[51]
	Osborne et al[52]
	Pederson et al[54]
	Ricard et al[55,56]
	Scheuffelen et al[58]
	Schmitt et al[59]
	Sheth et al[60]
	Shima et al[61]
	Zhang et al[64]
Runway	McLoda & Hansen[29]
	Nieuwenhuijzen et al[51]
	Ty Hopkins et al[62]
Fulcrum	Ubell et al[27]
	Ashton-Miller et al[28]
	Knight & Weimer[31]
	Anderson et al[32]
	Ottaviani et al[53]

Results

In this review, 46 journal articles about tilt platforms, trapdoors, and dynamic fulcrum devices, published during 1981−2012, were included.[20−64] Researchers have employed these instrument to perform motion tasks, including standing, step down, jump landing, and walking, in order to determine internal and external effects on simulated sprain conditions.[21−26,28,32−39,41,46−52,54−64] Internal aspects including muscle activation and sensorimotor influences, and external protectors such as taping and bracing were evaluated. Besides, the effects of training intervention were assessed. These simulators mimic incorrect landing postures, inversion or supination, which are susceptible to inversion sprain injury. The aim of this review is to summarise all reported sprain simulators in terms of their inversion angles, inversion velocities, supination angles, and appearances.

Discussion

Inversion angles

The first study that employed a tilt platform was conducted by Sprigings et al.[20] The inversion angles generated by all reported trapdoors, tilt platforms, and fulcrums ranged from 15° to 50° (see Table 2).[20−64] A real injury may take place if the inversion angle exceeds 35°.[21,22] An inversion of 35° was recorded in an accident that occurred in the laboratory,[18] compared to an inversion of 48° in an international competition.[65] The injury severity depends on the intensity of a motion. Most of the simulators could produce $<$ 30° inversion tilt, which was safe and ethical. However, Vaes and coworkers[25,26] had developed a platform that could generate a unilateral inversion at 50° from a risky preparation of plantarflexing at 40° and internally rotated at 15°. Researchers claimed that the 50° simulation was completely harmless. No conclusion could be made on the minimum inversion angle causing an ankle lateral ligamentous sprain.

Inversion velocities

Based on the fact that speed contributes to the injury severity, Lynch and colleagues[23] were the first to use a tilt platform that had two kinematic controls to investigate if uninjured participants showed muscles latency. The platform could give an

Table 2
Inversion angle of all ankle sprain simulators, including trapdoors, tilt platforms, and fulcrum devices.[a]

Authors	Inversion (°)	Appearance
Isakov et al[43]	20	A special apparatus that enables generation of sudden inversion. One rotating platform with a fixed platform was used.
Sheth et al[60]	20	A customised platform; one-half of the platform has a hinged trapdoor that can produce 20° of inversion, while another half was a scale ensuring 20% weight bearing of the foot.
Osborne et al[52]	20	
Anderson et al[32]	22	A wooden tilt platform with a tiltable surface used to invert one foot; the participant had to position the entire body weight on the right foot placed on the tiltable surface.
Ubell et al[27]	24	The fulcrum was 27 mm high & caused a maximum shoe sole inversion of 24° when the outer edge of the shoe sole touched down on a hard, level support surface.
Grüneberg et al[41]	25	A landing surface consists of a box with a trapdoor for the left foot and the box for the right foot is in the same dimension and material. A resistance of 200 g is needed for the first visible rotation & 2300 g for a rotation of 25°.
Shima et al[61]	25	A trapdoor was released & dropped at an angle of 25° with the horizontal plane. A participant was instructed to place one foot on the platform & rest the other foot on another platform of the same size & height. The space between the feet was ~20 cm. We instructed the participants to have their body weight distributed equally on both feet.
Knight & Weimar[30]	25	A fulcrum sole, 6 mm thick & 30 mm high, was placed at 20 mm from the medial border & ran the length of the outer sole; it could generate 25° of inversion.
Knight & Weimar[31]	25	
Sprigings et al[20]	30	An ankle inverter platform consisted of a raised platform, which had a hinged trapdoor built into it. The trapdoor could be manually activated to collapse at an angle of 30° below the horizontal. Approximately 2 N force was needed for the trapdoor to collapse.
Konradsen & Ravn[46]	30	A trapdoor capable of tilting to 30° in the frontal plane. Weight was evenly distributed on 2 feet.
Konradsen et al[47]		
Karlsson & Andreasson[44]	30	A manual activation ankle inverting platform with a trapdoor mechanism. Two platforms were placed 25 cm apart, allowing the participant to distribute body weight equally on both plates.
Lofvenberg et al[48]	30	A hinge trapdoor with two movable platforms that could be tilted to 30° in the frontal plane. The platform was released by an electrically powered motor.
Eils & Rosenbaum[40]	30	Custom-designed ankle inversion platform, with both feet being fixed on independently movable trapdoors. Each footplate was positioned at 40° PF, with the shoe at 15° of adduction. The operator then imposed a sudden 50° of inversion.
Nieuwenhuijzen et al[51]	30	A mechanically induced trapdoor box, which was 35 cm long, 20 cm wide, & 10 cm high. A spiral spring kept the trapdoor on top of the box in neutral position. A resistance of 200 g was needed to tilt the door to 0.1° & 2300 g for ° rotation. The trapdoor could tilt up to 30°.
Myers et al[50]	30	An ankle inversion perturbation device allowed the ankle joint to drop from a neutral position to 30° inversion when the participant was standing. The inversion velocity was ~440°/s. The participant was instructed to ensure equal weight distribution between the 2 limbs.
Ty Hopkins et al[62]	30	A trapdoor mechanism built into a runway was used for the walking trials. The runway consisted of five 1.22 m interchangeable segments, with the trapdoor mechanism incorporated into 1 segment.
Chan et al[34]	30	A pair of supination sprain simulators consisted of an L-shaped supporting frame, which was 0.34 m wide & 0.25 m high. A rotating disc on top of the platform allowed angle adjustment.
Zhang et al[64]	30	A custom-built trapdoor inversion platform could invert the ankle to 30°.
Scheuffelen et al[58]	20/30	A tilt platform could generate either 20° or 30°of inversion.
Kimura et al[45]	35	A 35° inversion platform allowed for a comfortable stance position & a normal base of support. A ledge was placed on the lateral side to prevent foot slippage.
Nawoczenski et al[21]		
Johnson & Johnson[22]	35	An electrically released special apparatus could produce inversion of either ankle. A solenoid was placed on either side of the apparatus to control foot-plate release mechanism. An adjustable sidebar was put laterally to block the foot.
Pederson et al[54]	35	An inversion platform that could produce 35° of inversion. The participant was instructed to balance on right foot by putting all the weight on the right side.
Cordova et al[35]	35	A custom-made inversion platform to produce inversion movement.
Cordova & Ingersoll[36]		
Ricard et al[55,56]	35	An inversion platform with a foot-support base that rotated by 35° after a trapdoor was released. A side bar on the right platform was used to ensure shoe position. The participants were instructed to put all their weight on the right foot, using the toes of the left foot to maintain balance, before & after the dropping of platform.
Eechaute et al[39]	Preparation: 40° PF & 15° adduction 50° IV	Custom-designed ankle inversion platform, with both feet fixed on independently movable trapdoors. Each footplate was positioned at 40° plantarflexion, with the shoe at 15° of adduction. Operator then imposed a sudden 50° of inversion.

PF = plantarflexion; IV = inversion.
[a] The devices are in ascending order with respect to the inversion angle.

inversion of 18° at a peak velocity of 446°/s. Study participants needed to prepare themselves in neutral position or plantarflexing their ankles in 20°. The inversion velocity could be controlled to either 50°/s or 200°/s. Four scenarios were simulated: 0° plantarflexion at 50°/s, 20° plantarflexion at 50°/s, 0° plantarflexion at 200°/s, and 20° plantarflexion at 200°/s. This allowed simulation at different intensities by varied combinations of ankle movements at different speed. Two other studies measured the inversion velocities when testing. The platform used by Ricard et al[55] could produce a speed of up to 517°/s. Knight and Weimar[30] introduced a fulcrum device, which could generate velocities in the range of 573−625°/s. This range of speed is similar to the intensity of the injury that occurred in international competition.[65]

Supination angles

Wright et al[16] proposed that touchdown plantarflexion increases the occurrences of an ankle inversion sprain. A plantarflexed ankle refers to a foot contacting the ground with the toes or forefoot. This motion increases the moment arm among the subtalar joint axis and thus the joint torque, followed by a sudden explosive twisting motion, and thus an ankle inversion sprain occurs.[66] Simulators that can initiate multiplane motion allow us to have a better understanding of ankle supination sprain kinematics (see Table 3).

Several platforms needed the participants to be at a plantarflexed position before the unexpected tilting.[23,25,26] The participants were at high risk and unstable positions; thus, these platforms could narrow the gap between subinjury trials and injury cases.

The ankle consists of the talocrural joint and the subtalar joint.[1] When these two joints work together, the ankle could either supinate or pronate. The suggested ankle sprain injury mechanism was inversion, plantarflexion, and internal rotation.[9] Every sprain motion is different, and does not occur only on one single plane purely but is accompanied by the other two planes.[34] The most flexible simulators were developed by Chan et al[34] (Figure 1A and B). A rotating disc was added on top of the platforms; different supination situations could be simulated accordingly (see Figure 2A and B). They reported ankle kinematics when the ankle was forced to have pure inversion of 30°; supination of 23°, 45°, and 67°; and pure plantarflexion. The study design and device were approved by Joint Chinese University of Hong Kong-New Territories East Cluster Clinical Research Ethics Committee.

Tilt platform in runway

Ankle sprains occur in dynamic situations, including walking, running, inappropriate jump landing, and stepping on uneven surfaces, rather than in standing situation, with both feet bearing the weight. Ankle sprain mostly occurred during systematic loading and unloading, but not when the ankle was fully loaded because of the anatomical restraints.[67] Nieuwenhuijzen and colleagues[51] put a trapdoor box on a treadmill. The left ankle of the study participants might invert when walking. A velocity of 403°/s was measured, which is close to

Table 3
Supination angle of all ankle sprain simulators, including trapdoors, tilt platforms, and fulcrum devices.

Author	Supination	Appearance
Ottaviani et al[53] Ashton-Miller et al[28]	15° IV & 0° or 16° or 32° PF	A specially designed testing apparatus forced the right ankle of each participant to invert 15° at 0°, 16°, 32° of plantarflexion. The apparatus consisted of a shoe securely fastened to a 1.5 cm thick 36 × 20 cm^2 board, with a track accommodating a 40 cm long 5 × 10 mm^2 steel bar underneath.
Lynch et al[23]	Preparation at 0° or 20° PF	A tilt platform achieved a tilt by a hydraulic activator. Velocity & magnitude could be adjusted. Preparation position could be either at neutral or at 20° of plantarflexion. The velocity could also be adjusted to 50°/s or 200°/s
Podzielny & Henning[24]	26° sideway 13° PF	A metal platform with foot plantarflexion, adduction, & inversion motions. A special release mechanism could drop the right platform to an angle of 26° sideways & 13° of plantarflexion. The abduction angle of the foot during standing was 23°. The left platform was used for balancing.
Lohrer et al[49]	30° IV & 15° PF	An inversion tilt platform induced 30° of inversion & 15° of plantarflexion. The participant was instructed to put 90% of body weight on the right foot.
Ricard et al[55,56]	37° IV & 15° PF	An inversion platform with a foot-support base that rotated 37°after a trapdoor was released. To help simulate the mechanism of sprain, the back of the inversion platform was raised to allow the subject to be tested at 15° of plantar flexion. The participant was asked to balance on the right side.
Chan et al[34]	Pure IV to pure PF	A pair of supination sprain simulators consisted of an L-shaped supporting frame(0.34 m wide & 0.25 m high). A rotating disc on top of the platform allowed angle adjustment.
Schmitt et al[59]	30° IV & 15° PF & 24° supination	A custom-made tilting platform allowed simulation of an inversion movement of 30° of effective perturbation angle. The built-in rotation axis permitted solely an inversion movement composed of a 15° of plantarflexion & a 24° supination movement.
Vaes et al[25,26] Eechaute et al[38]	Preparation at 40° PF & 15° adduction 50° inversion	A sprain simulation platform needed participants to place their right foot fixed on a rotation pulley & the ankle was at 40° of plantarflexion & 15° of adduction. The foot & ankle were stressed in inversion using a 15 kg load that internally rotated the pulley.

PF = plantarflexion; IV = inversion.

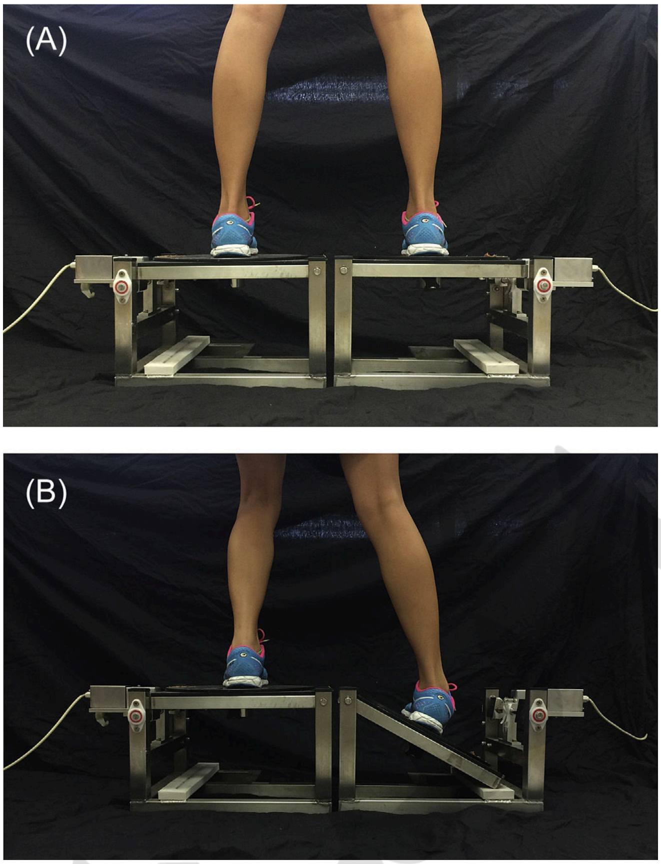

Figure 1. (A) A participant, in preparation, standing on the tilt platforms. (B) The right platform was tilted at 30°, forcing the participant to invert the right ankle. *Note*. Ankle inversion simulator was fabricated by Chan et al.[34]

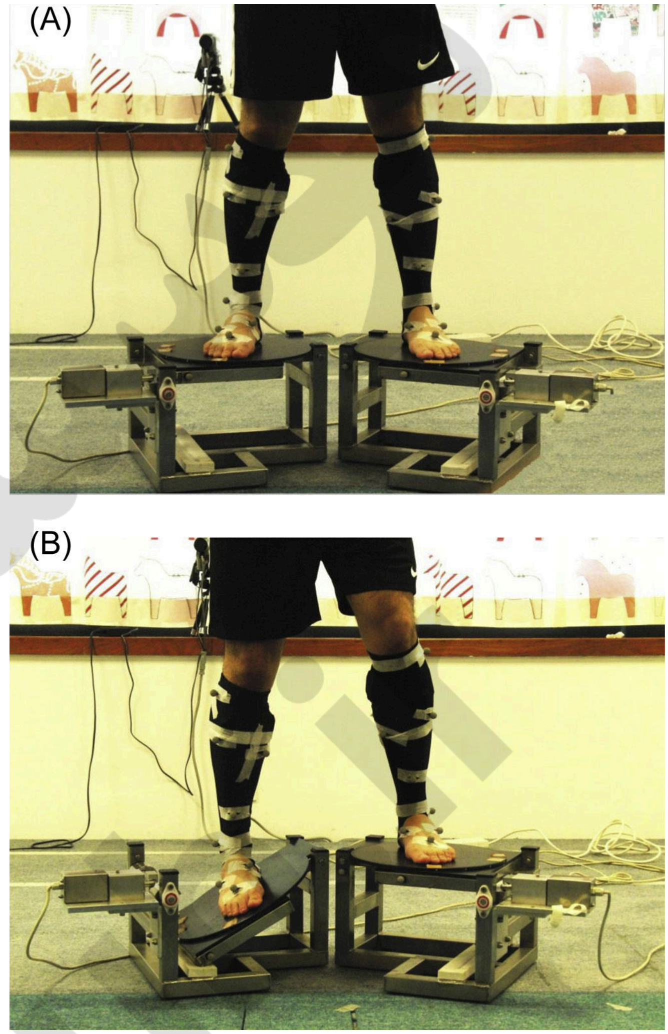

Figure 2. (A) A participant in preparation standing in the middle of the tilt platforms. Frames of both platforms were rotated to generate a combination of inversion and plantarflexion. (B) The participant was forced to supinate the right ankle. Frames of both platforms were rotated to generate a combination of inversion and plantarflexion. *Note*. Ankle inversion simulator was fabricated by Chan et al.[34]

the real injury inversion velocity. The participants might expect an inversion in this test, as the only trapdoor on the left was placed on the treadmill.

McLoda and Hansen[29] put an inversion platform in a runway. Five interchangeable segments were placed in the runway, one of them being an inversion platform. Researchers randomly placed the platforms in one of the segments. Either the left or the right ankle of the study participants might be tested when walking. A pressure of 0.45 kg applied to the platform could trigger the inversion of the platform.

Fulcrum sole

Ankle sprains rarely occur in a person with equal weight distribution on both feet. The fulcrum device was developed by Ubell et al.[27] It is a device that generates inversion speed by participants' weight instead of depending on the mechanical tilt. An unexpected inversion experiment was performed by using either a flat dummy sole or a fulcrum sole to simulate foot inversion movement. A fulcrum, 27 mm high and 6 mm wide, was attached to a sole at 20 mm medial to the midline. This could increase the rapidity and magnitude of simulation. The ankle ligaments might exceed the stretching tolerance if the subtalar joint inverts more than 30°.[28] Therefore, the inversion angle produced by this fulcrum sole design was limited to 24°. Either a flat dummy sole or a fulcrum sole was attached to the shoe when the participant was seated with their eyes closed.

Another fulcrum sole was developed by Knight and Weimar[30,31] based on Ubell et al's[27] design. They used a similar fulcrum, which was 30 mm high, 6 mm thick, placed 20 mm from the medial border, and was of the same length as that of the outer sole. This fulcrum could produce a 25° inversion. The sole with fulcrum was 0.178 kg, while the flat one weighed 0.134 kg. Both had similar weights in order to prevent estimation. The participants were instructed to step down on a metal surface from a high block. The inversion velocity was calculated during data processing. The sole could reach a speed of 625°/s for an injured ankle and 573°/s for an uninjured ankle. Compared to the slowest inversion velocity (632°/s) recorded in a real tennis match,[68] this fulcrum device could produce a very-close-to-injury scenario.

Table 4
Inversion velocity of all ankle sprain simulators, including trapdoors, tilt platforms, and fulcrum devices.[a]

Authors	Inversion (°)	Inversion velocity	Appearance
Lynch et al[23]	18	50°/s or 200°/s (controlled)	A tilt platform achieved a tilt by a hydraulic activator. Velocity & magnitude could be adjusted. Preparation position could be either at neutral or 20° of plantarflexion. The velocity could also be adjusted to 50°/s or 200°/s.
Ricard et al[55,56]	37	Up to 517°/s in measurement	An inversion platform with a foot-support base that rotated 37° after a trapdoor was released. To help simulate the mechanism of sprain, the back of the inversion platform was raised to allow the subject to be tested at 15° of plantar flexion. The subject was asked to balance on the right side.
Nieuwenhuijzen et al[51]	30	Walking: 403°/s Jumping: 595°/s	A mechanically induced trapdoor box, which was 35 cm long, 20 cm wide, & 10 cm high. A spiral spring kept the trapdoor on top of the box in neutral position. A resistance of 200 g was needed to tilt the door to 0.1° & 2300 g for a rotation of 25°. The trapdoor could tilt up to 30°.
Knight & Weimar[30]	25	573–625°/s in measurement	A fulcrum sole, 6 mm thick & 30 mm high, was placed at 20 mm from the medial border & ran the length of the outer sole; it could generate 25° of inversion.

[a] The devices are in ascending order with respect to the inversion velocity.

Conclusion

Biomechanical researchers have been using trapdoors and tilt platforms to simulate ankle inversion motion in laboratories to study inversion sprain injury mechanism. These tools had different settings and appearances. The objectives of passive tests included studying the peroneal latency,[20–23,25,26,29,31,33–38,40–44,46,48–52,57] and investigating the effect of external ankle bracings,[20,24,25,27,28,32,34,35,42,43,55,58,60] taping,[28,31,49,54,55,61] the effects of training interventions,[40,52,60] and sensorimotor influence of the lateral ankle ligaments.[40,42,49,50] Trapdoors were also being placed in runways to perform walking tests.[50,51,62] Fulcrum removable sole was another design which attached beneath the shoes. Researchers would put a fulcrum sole or a dummy sole beneath participants' shoes before performing jump-landing and step-down tasks as these motions are prone to ankle inversion sprains in sport events.[30,31] These tools allowed researchers to understand the injury mechanism and causes of injury, and thus to improve the existing preventive appliances. Inversion angle was being seen as the only motion in early designs, but ankle sprain is not a single-plane motion. All tilt platforms and fulcrum devices included in this article were reported to show a tilt range of 15–50°. Inversion speed can affect the severity of injury, as our peroneal muscles cannot respond fast enough in order to correct the ankle orientation. Therefore, researchers started to control the inversion velocity of simulators to a more realistic situation. The inversion velocities ranged from 50°/s to over 600°/s (see Table 4). Some platforms were able to produce multiplane motions, including supination or plantarflexion, to simulate the motion to a more realistic extent.

The major limitations of studying sports injury in biomechanics laboratories are safety and ethical issues. All simulators have their strengths and weaknesses. To simulate an injury close to reality, motions including walking, jump-landing, and step-down tasks are highly recommended. Both supination angle and velocity should be considered when developing a simulator.

Summaries of this review

(1) Ankle inversion ligamentous sprain is very common in sports events but rare in laboratories. It is unethical and impractical to sprain living persons' ankles intentionally.[65] Trapdoors, tilt platforms, and fulcrum devices were fabricated to mimic the sprain motion in laboratories.
(2) A supinating platform consisting of both inversion and plantarflexion motions would be a better option for researchers to study ankle supination sprains.
(3) Inversion velocity contributes to the ankle inversion sprain injury. In order to produce a close-to-injury velocity in a laboratory on test participants, researchers may consider using the weight of the participants to generate the speed instead of depending on the machine to do so.

Conflicts of interest

The authors have no conflicts of interest relevant to this article.

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