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In vitro analysis of muscle activity illustrates mediolateral decoupling of hind and mid foot bone motion

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ABSTRACT

Activity of the extrinsic ankle–foot muscles is typically described for the whole foot. This study determines if this muscle activity is also confirmed for individual foot segments defined in multi-segment foot models used for clinical gait analysis. Analysis of the individual bone motion can identify functional complexes within the foot and evaluates the influence of an altered foot position on muscle activity. A custom designed and built gait simulator incorporating pneumatic actuators is used to control the muscle force of six muscle groups in cadaveric feet. Measurements were performed in three static postures in which individual muscle force was incrementally changed. The motion of four bone embedded LED-clusters was measured using a Krypton motion capture system and resulting motion of calcaneus, talus, navicular and cuboid was calculated. Results indicate that primary muscle activity at bone level corresponds with that described for the whole foot. Secondary activity is not always coherent for bones within one segment: decoupling of the movement of medial and lateral foot bones is documented. Furthermore, secondary muscle activity can alter according to foot position. The observed medio-lateral decoupling of the foot bones dictates the need to extend some of the multi-segment foot models currently used in clinical gait analysis.

1. Introduction

Anatomical studies typically document muscle activity considering the foot as one rigid segment rotating around the ankle and subtalar joints in unloaded or loaded conditions [1–4]. These studies therefore provide only limited information on kinematics of individual foot joints. Biomechanical studies use multi-segment foot models to document kinematics of fore-, mid- and hind foot segments during gait. Several foot bones are combined in one segment and none or minimal motion between bones of each segment is assumed [5–7]. Using this approach, characteristic movement between foot segments has been described during gait, as well as changes in these patterns due to pathologic conditions [8–10]. However, medical imaging and in vitro studies clearly demonstrate motion between bones belonging to one foot segment [11–13]. Since it is known that in clinical conditions (e.g. flexible flatfoot), the mobility of individual foot bones is significantly altered, there is a need to document muscle activity at the level of individual segments and even individual bones. This will result in a better understanding on how muscle imbalance contributes to these conditions.

Non-invasive, in vivo measurements do not allow to study the role of muscle activity on individual bone kinematics as this would require the tracking of three skin-mounted markers on each individual bone. Furthermore, isolated muscle activation can seldom be induced [14]. In vitro studies allow assessment of individual foot bone motion using bone pins and allow controlled forces to be imposed on individual muscle actuators. Using this approach, previous research typically focused on specific clinical questions in static and dynamic conditions [15–19], but did not exhaustively document muscle activity on individual foot bone motion. Using a gait simulator that loads musculo-tendinous structures, a gait-like motion can be generated and foot bone kinematics can be measured [20–22]. Although technically feasible, only a limited number of in vitro studies explicitly explored the effect of individual muscle activity on bone motion [23–26]. Kim et al. described the unique role of the individual extrinsic foot muscles on center of pressure but did not report individual bone kinematics. Niki et al., Blackman et al. and Wülker et al. reported the effect of Tibialis posterior, Triceps surae and Tibialis anterior muscles on individual foot bone motion.

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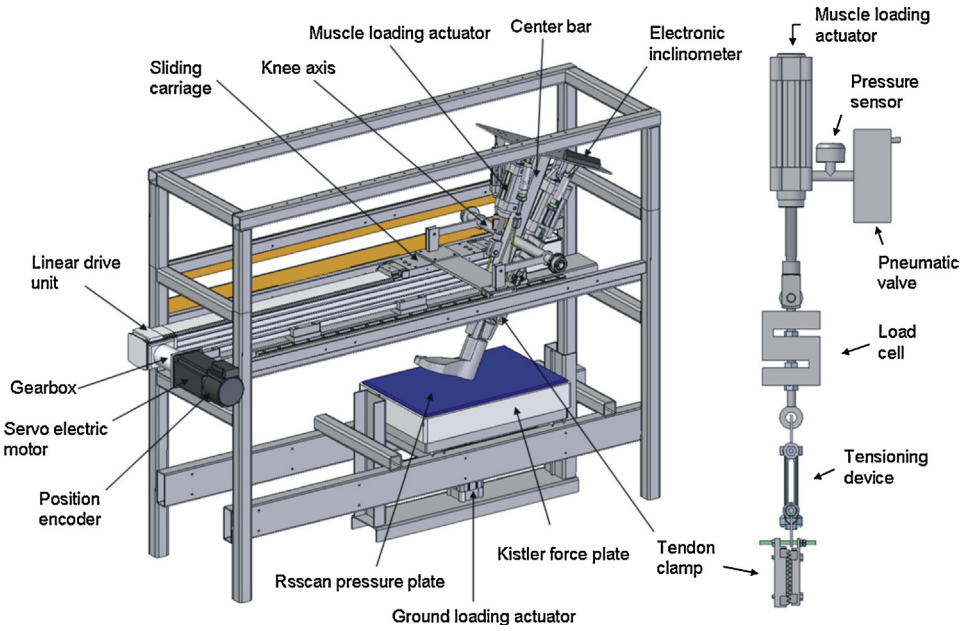

Fig. 1. Design of the in vitro dynamic gait simulator. The simulator consists of a general framework, carrying the actuator bearing frame. The actuators apply loads to a foot, mounted in the center of the actuator bearing frame. A sliding carriage, driven by a servo electric motor drives the foot through the stance phase of gait.

The aim of this study was (1) to determine if muscle activity, as described for the whole foot, is confirmed for individual foot segments as used in clinical gait analysis, (2) to assess the influence of altered foot positions on muscle activity, and (3) to determine the need to differentiate muscle activity within foot segments and consider muscle activity on individual bones, therefore identifying functional complexes of the foot.

2. Materials and methods

2.1. Specimen preparation

Five fresh frozen cadaver specimens, voluntarily donated for scientific research, were tested in a custom designed and built gait simulator (Fig. 1). Following amputation, the feet were kept frozen and brought to room temperature in tepid water before handling and testing. The lower leg was transected at mid-tibial level and imbedded in a cylinder, fitting over the tibia, using polyester resin (Motip Dupli B.V.). This cylinder extends the tibia and allows mounting of the foot in the gait simulator. The tendons of nine extrinsic leg muscles were released, leaving retinaculae, capsules and ligaments intact to prevent interference with the muscles' natural trajectory. The following tendons were grouped in six functional equivalents according to Bogey et al. [27]: triceps surae, peroneal muscles (longus and brevis), pretibial muscles (extensor digitorum longus, extensor hallucis longus, tibialis anterior), tibialis posterior, flexor hallucis longus and flexor digitorum longus. To accommodate the attachment of LED clusters for 3D motion analysis, titanium intracortical pins (diameter: 4 mm, length: 50 mm, ICOS, New Deal, France) were inserted in the talus, calcaneus, navicular and cuboid and rigidly secured in the bone with a two component epoxy glue. A custom-designed stabilizing device provided extra stability and prevented axial rotation through three attachment points within the bone (Fig. 2). Anatomical integrity of the cadaveric feet and correct placement of the pins were evaluated by a 0.5 mm spiral CT (Aquillion 64, Toshiba Medical Systems B.V., Japan). These CT scans were also used to define the local anatomical reference frames for kinematic analysis.

2.2. Gait simulator

The gait simulator consists of a framework carrying pneumatic actuators that apply force to the tendons of the extrinsic foot–ankle muscles. The force magnitude was calculated based on kinematics and ground reaction forces, measured during a gait analysis trial in a control subject (female, 47.9 kg). Using a musculoskeletal model, inverse dynamics and a static optimization algorithm, the muscle force distribution problem was solved and individual muscle forces during stance were calculated for all relevant muscles [28]. To allow appropriate dimensioning of muscle forces to actuator capacity, forces were scaled to a body weight of 245N (25 kg). Nylon tendon clamps preventing tendon slippage but allowing application of high forces (1800N) connected the tendons to the actuators. Load cells in series with the actuators measured the actual force applied to the tendons.

The foot was mounted into the simulator by connecting the surrogate tibia to a bar in the center of the device. A force plate (Kistler Multicomponent Force Plate, Kistler Instruments GmbH) supported the foot and varied the force applied by a pneumatic actuator underneath the plate similar to the vertical GRF. All control software was programmed in Labview 8.2 (National Instruments, Austin, Texas, U.S.) and Matlab 7.1 (Mathworks, Natick, Massachusetts, U.S.). For a detailed description on technical specifications of the device, we refer to [29].

2.3. Measurement devices

Motion of the foot bones was tracked using a Krypton optoelectronic motion capture system (Krypton K600, Metris, accuracy: 90 micron, sampling frequency: 100 Hz) using five rigid bone-mounted clusters, each containing four active

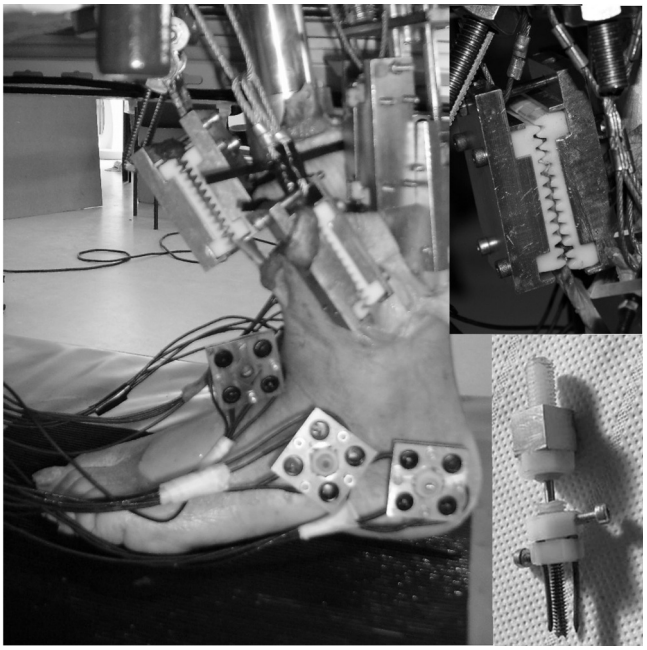

Fig. 2. Foot, mounted in the gait simulator. Custom built clamps are attached to the tendons of the six muscle groups. A detail of one clamp is shown in the top right of the image. The marker clusters, from which three are visible, are also present. A detail of an intracortical pin with a stabilizing device is shown in the bottom right corner.

Table 1
Equilibrium forces for all muscle groups and the vertical ground reaction force at P1, P2 and P3. These values represent the reference values from which is started to perform an isolated contraction of a muscle group. Maximal force and the force increase with each step are presented as well.

	Equilibrium forces at P1 [N]	Equilibrium forces at P2 [N]	Equilibrium forces at P3 [N]	Maximal force [N]	Force increase with each step [N]
M. Triceps surae	464	442	891	2270	145
Pretibial muscles	521	427	138	825	40
Mm. Peronei	182	263	110	345	40
M. Tibialis posterior	42	16	84	205	40
Vertical ground reaction force	208	289	311	/	/

markers. The Kistler force plate measured the three ground reaction forces and moments (sampling frequency: 1000 Hz).

2.4. Protocol

Three foot postures, relevant to gait, were examined: position 1 (P1) represents heel strike with the shank tilted to 12° and the foot in neutral position, position 2 (P2) represents midstance with the foot flat and tibia perpendicular to the ground and position 3 (P3), represents heel rise, with the foot in plantarflexion. For each position, a position-specific force equilibrium was applied (Table 1). Thereafter, the force magnitude of one single pneumatic actuator was increased stepwise, simulating individual muscle contraction. Each step was maintained until a new force equilibrium was reached (Table 1). This was repeated twice for each muscle group in all three foot positions.

3D kinematics were calculated in Matlab 7.1. A global axes system was defined, coinciding with one of the corners of the force plate. For each bone, a local reference frame was defined, based on a set of three anatomical landmarks (Table 2). The landmarks defined the plane of the coordinate frame to which the third axis was defined perpendicularly. The axes of each local frame were then projected into planes of the global system. The 3D bone rotations were derived from the angle between the projected axis and the global axis system. Varus and valgus motion were defined around the anteroposterior axis (*X*-axis), plantar- and dorsiflexion around the medio-lateral axis (*Z*-axis) and internal- and external rotation around the dorso-plantar axis (*Y*-axis). The magnitude of bone rotation as a function of 100N force increase parameterized the slope of the force–rotation curve. This analysis was repeated for all three foot positions. Due to the small sample size, data were handled in a descriptive way. Given the known variability in cadaveric experimentation, variability of rotation direction was quantified based on the percentage of measurements presenting rotation in the one or other direction. If the percentage was below 60%, the measurement was excluded from further analysis. Mean values of rotation were calculated for the remaining trials.

3. Results

Table 3 presents an overview of the results. Although the direction of bone rotation was our primary interest, the rotation magnitude was also quantified. These rotations result from the force increase of one isolated muscle perturbing the reference muscle force equilibrium for a specific foot position. Consequently, only rotation due to this additional force increase is quantified, therefore accounting for the differences in rotation magnitude reported in the current and published, dynamic studies [21].

- The pretibial muscle group has a consistent dorsiflexion and external rotation activity in all three foot positions. Varus is seen at talus, navicular and calcaneus at P1 and at talus and navicular at P2.
- The activity of Triceps surae muscle induces plantarflexion of all bones in all three foot positions. In the frontal plane, valgus is induced with the exception of the calcaneus and cuboid that perform a varus motion at P3. Transverse plane motion is more variable: internal rotation is present for the calcaneus, navicular and cuboid at P1 and the calcaneus, cuboid and talus at P3, while external rotation is seen for the talus at P1 and P2 and for the navicular at P2 and P3.
- The Tibialis posterior induces varus in all bones for all foot positions. Plantarflexion is seen at P1 in all bones. This function is less apparent at P2 presenting dorsiflexion of the navicular and during P3 presenting dorsiflexion of navicular and talus. A similar effect is seen for motion in the transverse plane: internal rotation is seen during P1 and P2 in all bones but this activity changes in external rotation during P3.
- The Peroneal muscles induce valgus of all bones in all positions. External rotation is seen at P1 but more variable transverse plane motion is seen at P2 (internal rotation of calcaneus, navicular/external rotation of talus and cuboid) and P3 (internal rotation of calcaneus, navicular/external rotation for talus). For all bones, motion in the sagittal plane changes from plantarflexion at P1 to dorsiflexion at P2 and P3.

4. Discussion

This study reports the activity of four main muscle groups on individual bone kinematics of the hind- and midfoot. It therefore documents muscle activity at a more detailed level compared to previous studies focusing on the whole foot or even on the foot as a multi-segment structure. As such, we investigated if the rigid segment assumption that underlies multi-segment foot modeling used for clinical gait analysis, is a valid assumption. Furthermore, by comparing muscle activity in three different foot positions, this study provides information on the position dependent functional coupling of bone motion.

In our study, primary muscle activity corresponded with that described for the whole foot [2]. Similar muscle activity was found for all foot bones in all three foot positions. This indicates that the current grouping into foot segments is adequate for research on

Table 2
Bony landmarks for anatomical co-ordinate frame definition.

Bone	Origin	Landmark 1	Landmark 2	Landmark 3
Talus	Tip of the posterolateral tubercle	Center of the talar head	Tip of the lateral process	Tip of the posterolateral tubercle
Calcaneus	Point between lateral and medial tuberosity on the inferior surface	Sinus tarsi (intersection of the bifurcate ligament)	Point between lateral and medial tuberosity on the inferior surface	Point on the anterior tuberosity of the inferior surface
Cuboid	Most posterior point on the anterior border of the dorsal surface	Most anterior point on the anterior border of the dorsal surface	Most posterior point on the anterior border of the dorsal surface	Most plantar point of the inferior border of the posterior surface
Navicular	Center of the navicular cup	Center of the navicular cup	Tip of the medial border of the dorsal surface	Tip of the lateral border of the inferior surface

Table 3
Results for all muscle contractions and all foot positions tested. Motion around the *X*-axis is considered valgus (Val, positive value) and varus (Var, negative value). Motion around the *Y*-axis is considered external rotation (Er, positive value) and internal rotation (Ir, negative value). Motion around the *Z*-axis is considered dorsiflexion (Df, positive value) and plantarflexion (Pf, negative value). The '%' expresses the percentage of measurements that resulted in the given rotation. Primary muscle activity is reflected in bold.

	P1			P2			P3		
	X	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*
Triceps surae									
Cal rotation	Val	Ir	**Pf**	Val	Ir	**Pf**	Var	Ir	**Pf**
[°/100N]	0.69	−1.41	**−4.83**	0.22	−0.14	**−0.84**	−0.21	−0.66	**−1.37**
%	60	90	**100**	67	89	**89**	75	88	**100**
Tal rotation	Val	Er	**Pf**	Val	Er	**Pf**	Val	Ir	**Pf**
[°/100N]	4.6	0.20	**−5.66**	0.44	0.32	**−0.30**	1.7	−0.28	**−1.74**
%	90	60	**90**	89	56	**78**	75	75	**63**
Nav rotation	Val	Ir	**Pf**	Val	Er	**Pf**	Val	Er	**Pf**
[°/100N]	0.84	−2.11	**−5.93**	0.26	0.36	**−0.64**	0.74	0.60	**−1.59**
%	80	70	**90**	78	67	**89**	75	63	**75**
Cub rotation	Val	Ir	**Pf**	Val	Ir	**Pf**	Var	Ir	**Pf**
[°/100N]	1.64	−4.06	**−4.81**	0.22	−0.17	**−0.53**	−0.35	−0.94	**−1.36**
%	63	100	**100**	89	67	**89**	71	86	**71**
Pretibial muscles									
Cal rotation	Var	Er	**Df**	Val	Er	**Df**	Val	Er	**Df**
[°/100N]	−0.06	0.22	**0.65**	0.09	0.27	**0.51**	0.00	0.30	**0.68**
%	57	86	**71**	63	75	**100**	50	70	**90**
Tal rotation	Var	Er	**Df**	Var	Er	**Df**	Var	Er	**Df**
[°/100N]	−0.41	0.45	**0.32**	−0.50	0.92	**0.36**	−0.33	0.51	**0.44**
%	67	67	**100**	100	71	**100**	63	63	**88**
Nav rotation	Var	Er	**Df**	Var	Er	**Df**	Var	Er	**Df**
[°/100N]	−0.25	0.26	**0.73**	−0.44	0.00	**0.72**	−0.29	0.95	**1.12**
%	71	71	**86**	100	50	**100**	100	70	**100**
Cub rotation	Val	Er	**Df**	Val	Er	**Df**	Val	Er	**Df**
[°/100N]	0.06	0.65	**0.82**	0.18	0.35	**0.46**	0.15	0.66	**0.65**
%	80	100	**80**	63	100	**100**	90	90	**100**
Peroneal muscles									
Cal rotation	**Val**	Er	Pf	**Val**	Ir	Df	**Val**	Ir	Df
[°/100N]	**0.97**	0.57	−0.17	**0.44**	−0.27	0.15	**0.49**	−0.67	0.13
%	**90**	100	80	**89**	89	78	**90**	100	90
Tal rotation	**Val**	Er	Pf	**Val**	Er	Df	**Val**	Er	Df
[°/100N]	**0.41**	0.34	−0.85	**0.18**	0.96	0.96	**0.17**	0.60	0.60
%	**67**	89	89	**100**	71	71	**63**	75	63
Nav rotation	**Val**	Er	Pf	**Val**	Ir	Df	**Val**	Ir	Df
[°/100N]	**0.91**	0.62	−0.29	**0.52**	−0.19	0.05	**0.68**	−0.45	0.12
%	**80**	70	90	**89**	67	56	**80**	90	60
Cub rotation	**Val**	Er	Pf	**Val**	Er	Pf	**Val**	Ir	Df
[°/100N]	**0.53**	0.64	−0.30	**0.48**	0.30	−0.14	**0.74**	0.01	0.26
%	**83**	100	67	**100**	56	56	**100**	50	90
Tibialis posterior									
Cal rotation	**Var**	Ir	Pf	**Var**	Ir	Pf	**Var**	Er	Pf
[°/100N]	**−0.41**	−0.63	−0.23	**−0.16**	−0.07	−0.1	**−0.28**	0.39	0.01
%	**88**	88	88	**78**	56	78	**100**	83	50
Tal rotation	**Var**	Ir	Pf	**Var**	Ir	Pf	**Var**	Er	Df
[°/100N]	**−0.37**	−0.45	−0.29	**−0.15**	−0.19	−0.09	**−0.49**	0.29	0.09
%	**57**	57	100	**100**	56	78	**100**	100	71
Nav rotation	**Var**	Ir	Pf	**Var**	Ir	Df	**Var**	Er	Df
[°/100N]	**−0.69**	−0.87	−0.37	**−0.55**	−0.19	0.21	**−0.43**	0.33	0.14
%	**100**	88	63	**89**	89	78	**100**	75	75
Cub rotation	**Var**	Ir	Pf	**Var**	Ir	Pf	**Var**	Er	Pf
[°/100N]	**−0.49**	−0.77	−0.32	**−0.19**	−0.11	−0.08	**−0.28**	0.33	−0.23
%	**71**	100	86	**100**	78	89	**75**	75	63

normal and pathological primary muscle activity. The main activity was found to be dorsiflexion, plantarflexion, varus and valgus for contraction of the pretibial muscle group, Triceps surae, Tibialis posterior and Peroneï respectively.

However, secondary muscle activity was more variable and suggested a position dependent, mediolateral decoupling within the mid- and hind foot segments for specific muscle groups:

- For the pretibial muscle group, secondary muscle activity was variable between foot positions: e.g. internal rotation changes in external rotation at P2 and P3. Furthermore, secondary muscle activity resulted in opposite motion of the medial and lateral compartments: e.g. varus activity for all bone structures changes in valgus of the lateral foot compartment and induces opposite motion of calcaneus and cuboid within one foot segment at P2. This muscle activity differed from the external rotation reported in literature [26]. This relates to the difference between the combined activity of the extensor muscle group in this study, compared to the individual activity of Tibialis anterior reported in literature.
- For Triceps Surae, secondary activity in valgus at P1 and P2 contradicts the anatomy-based activity on the whole foot, i.e. varus and internal rotation [1,2]. The observed valgus activity was induced by the weight bearing of the heel at P1 and P2. As a

result, the calcaneus was positioned in valgus and directed the insertion of the Achilles tendon more laterally than the subtalar axis. This effect was no longer present at P3, where the heel lost contact with the ground and varus of the calcaneus and cuboid was induced. The medial foot compartment (i.e. talus and navicular) presented an opposite motion. Likewise, for transverse plane motion, external rotation of the talus and navicular was confirmed at P2 but internal rotation was found at the calcaneus and cuboid. This external rotation contrasted the in vitro study of Blackman et al. [25] who confirmed plantarflexion, valgus and internal rotation of all bones at P2 and did not observe opposite motion between the lateral and medial compartment.

- For the Tibialis posterior and Peroneï, secondary muscle activity was position dependent, changing from plantarflexion and ad- and abduction respectively at P1 to dorsiflexion and respectively ab- and adduction at P3. Our results do not agree with the sagittal plane motion, reported in the in vitro study of Niki et al. [24] due to altered movement constraints. These authors used a support underneath the foot in all three positions, whereas more natural foot contact without additional support was used in our study.

Based on this analysis, we conclude that for all four studied muscle(group)s, secondary muscle activity induced individual bone motion within segments defined as rigid.

Furthermore, secondary muscle activity of the Triceps surae and the pretibial muscles, induced a functional decoupling between the talus-navicular and the calcaneus-cuboid unit, respectively representing the medial and lateral foot column. This implies that the division of the foot into a rigid hind-, mid, and forefoot should be handled with care, especially in pathologic conditions, where the decoupling of the hind foot (talus and calcaneus) is even more apparent [12]. Mediolateral decoupling is mainly seen in muscle groups inserting along the anterior and posterior axis and is less pronounced in muscle groups inserting along the medial and lateral axis: Tibialis posterior and Peroneï present widespread attachment regions covering the midfoot bilaterally, therefore restricting mediolateral decoupling. The muscles inserting along the antero–posterior axis have only an indirect effect on the midfoot bones, therefore allowing mediolateral decoupling [2]. Furthermore, our study indicates that foot position influences secondary muscle activity and therefore observed functional decoupling of individual foot bones. This implies that functional foot complexes may vary across the gait cycle. The altered alignment of individual foot bones and the muscle trajectory is responsible: for each position, the foot sole is loaded differently, inducing movements in the direction of least resistance. Therefore, some of our results differ from muscle function described based on muscle trajectory that does not account for the effect of foot position, nor for foot loading. An example of this is the dorsiflexion activity seen with contraction of Peroneï at P2 and P3.

As with all cadaveric studies, there are limitations, intrinsic to the study set-up, including the small number of cadaver specimens, the lack of information on age, gender and body weight. Therefore, care should be taken when generalizing in vitro results to living subjects. Furthermore, intrinsic muscle activity is not incorporated in our simulator set-up. However, previous research reported limited differences in kinematics when comparing a dynamic in vitro study with an invasive in vivo study [30]. Furthermore, the grouping of the foot bones in a medial and lateral column, instead of a hind- and midfoot, is not feasible within clinical practice due to skin motion artifacts and the practical inability to position three markers on each bony segment of medial and lateral column. Therefore, this study strengthens the importance of future in vitro research on the effect of individual muscle activity on foot bone kinematics. Such in vitro data sets are essential to develop advanced modeling techniques that can assist in further increasing the accuracy of clinical measurements.

5. Conclusion

In conclusion, this study suggests that (1) muscle activity, as previously described for the whole foot, can only be confirmed for primary muscle activity on individual foot segments defined as used in clinical gait analysis. Confirmation of the secondary muscle activity varies depending on the segments studied.

(2) A similar trend is seen when altering foot position. No effect of altered foot position is seen for primary muscle activity, whereas secondary activity is influenced by foot position.

(3) Current use of foot segments is satisfactory to study primary muscle activity. However, for secondary muscle activity, current foot models are limited in accurately describing foot position dependent functional decoupling between the medial and lateral column of the foot.

Conflicts of interest

All authors declare there is no conflict of interest in any way. There was no financial and personal relationships with other people or organizations that could inappropriately influence (bias) the submitted work. The funding sources, as stated in the acknowledgements, had no involvement on study design and collection, analysis and interpretation of the data, neither in writing or decision to submit the manuscript for publication.

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