

# An in vitro study of individual ankle muscle actions on the center of pressure

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## Abstract

The objective of this study was to correlate the effects of muscle force on the movement of the center of pressure (COP) for increased clinical utility of the COP measurement. Five fresh frozen cadaveric specimens were used to apply a 49 N sinusoidal muscle force to isolated or grouped extrinsic ankle muscles, and a constant ankle joint reaction force at different tibial positions. The muscle force and the vertical ground reaction force (GRF) play the role of a mechanical lever system so that the differential COP movement can be interpreted as a moment arm for the vertical GRF.

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## 1. Introduction

Center of pressure (COP) is the centroid of the vertical force distribution on the plantar surface of the foot or the point location of the resultant ground reaction force (GRF) vector in the plane of the ground at which the GRF vector is considered to apply [1]. The COP has been included in many investigations of foot function. In gait analysis, the path of the instantaneous COP during stance is considered as the direct reflection of the patient's balance and pattern of progression [2]. Studies have described the path of the COP under the normal foot during the stance phase of gait as well as deviations in the COP associated with pathological conditions and their treatment [3–8]. Also post-treatment outcomes of various orthoses in terms of the COP movement during gait have been reported [9,10].

Along with the body's center of gravity (COG), the COP is particularly relevant to the biomechanical study of balance and postural control in man [11]. Its temporal changes are attributable to the kinematics and kinetics of the lower extremity, foot and ankle anthropometry,

and gait parameters [12,13]. The location of the COP is not a mere reflection of the COG onto the foot. Since the ankle muscles are primary controllers of the COP, the location of the COP is an outcome from concerted efforts of the individual ankle muscles [14]. Furthermore, the COP progression cannot be directly related to the foot function without having knowledge on its associations with the ankle muscles. Such knowledge is essential in order for clinicians to understand the implications of various treatment outcomes through clinical COP measurements [9] and for researchers to investigate neuromuscular control modeling and simulation of the lower extremity. Despite its importance on the neuromuscular control of the ankle joint and associated pathologies, little attention has been given to this ill-defined biomechanical problem due to multiplicity of the muscles around the ankle joint and lack of appropriate methods to quantify the contributions of the individual ankle muscles to the COP movement.

The objective of the current in vitro study was to measure the effects of six functionally-equivalent major ankle muscle groups on the COP movement using the previously developed dynamic gait simulator [15]. This study will provide better information on the physiologic implications of the COP movement with respect to the

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roles of the ankle muscle groups during posture and balance in man.

## 2. Methods

### 2.1. Theoretical considerations

For a simplified foot and ankle joint model with a constant vertical joint reaction force ( $F_J$ ) on the ankle (Fig. 1a), the force equilibrium in the horizontal (+x) direction upon the application of a small incremental muscle force  $\Delta f_i$  for muscle  $i$  (Fig. 1b) gives

$$-\Delta f_i \sin \theta_i + \Delta G_x^i = 0 \quad (1)$$

where  $\Delta G_x^i$  is the corresponding GRF change in the anterior–posterior (A–P) direction and  $\theta_i$  is the angle between the muscle line of action and the vertical. Similarly, the force equilibrium in the vertical (+y) direction before the application of the muscle force  $\Delta f_i$  (Fig. 1a) yields

$$-F_J - W_F + G_y = 0 \quad (2)$$

where  $W_F$  is a weight force of the foot mass, and  $G_y$  is a vertical GRF. After the application of the muscle force  $\Delta f_i$  (Fig. 1b), the new force equilibrium becomes

$$\Delta f_i \cos \theta_i - F_J - W_F + G_y + \Delta G_y^i = 0$$

$$\Delta f_i \cos \theta_i + \Delta G_y^i = 0 \quad (3)$$

where  $\Delta G_y^i$  is an increased GRF in the medio–lateral (M–L) direction due to the muscle loading. In addition, moment equilibrium about the ankle joint before the application of the muscle force  $\Delta f_i$  (Fig. 1a) gives

$$-r_F W_F + p_x G_y = 0 \quad (4)$$

where  $p_x$  is the initial COP in the A–P direction and  $r_F$  is the moment arm of the weight force  $W_F$ . After the application of the muscle force  $\Delta f_i$  (Fig. 1b), the moment equilibrium becomes

$$-\Delta f_i r_i - r_F W_F + (p_x + \Delta p_x^i)(G_y + \Delta G_y^i) + h \Delta G_x^i = 0 \quad (5)$$

where  $\Delta p_x^i$  is the differential COP movement (DCOP; COP changes from the initial location) in the A–P direction,  $r_i$  is the moment arm of the muscle  $i$ , and  $h$  is the vertical height of the ankle joint. By substituting Eq. (1), Eq. (2), Eq. (3), and Eq. (4) into Eq. (5) and neglecting a higher order term, the DCOP change for the given muscle loading becomes

$$\frac{\Delta p_x^i}{\Delta f_i} = \frac{r_i - h \sin \theta_i + p_x \cos \theta_i}{G_y} \quad (6a)$$

$$\frac{\Delta p_x^i}{\Delta f_i} = \frac{(F_J + W_F)(r_i - h \sin \theta_i) + r_F W_F \cos \theta_i}{(F_J + W_F)^2} \quad (6b)$$

$$\frac{\Delta p_x^i}{\Delta f_i} \approx \frac{r_i}{F_J} \quad \text{for } W_F \ll F_J \quad \text{and} \quad \theta_i \approx 0^\circ \quad (6c)$$

It is indicated that the DCOP, due to the given muscle loading, remains constant as long as the ankle joint reaction force remains constant and the muscle line of action remains parallel to the vertical. For multiple activation of the ankle muscles, the total change of the COP in the A–P direction is the sum of the individual DCOP, such that

$$\Delta p_x = \sum_i \Delta p_x^i \approx \sum_i \frac{r_i}{F_J} \Delta f_i \approx \sum_i \frac{r_i}{G_y} \Delta f_i \quad (7)$$

A similar relationship can be found for the COP in the M–L direction,  $p_z$ .

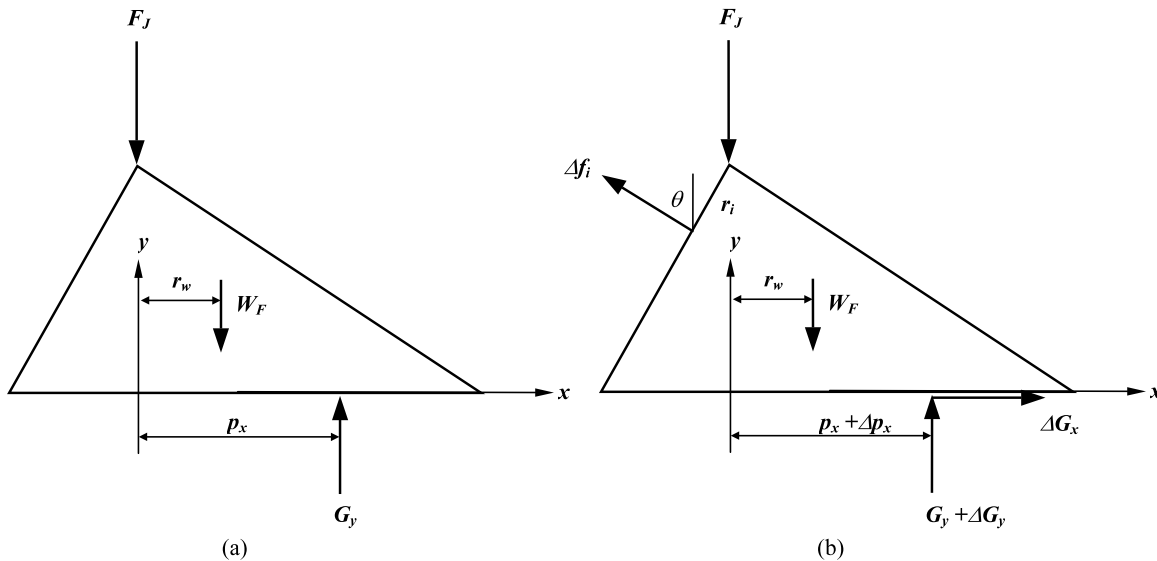


Fig. 1. A simplified model of the foot (a) before and (b) after the application of the small muscle force  $\Delta f_i$  for muscle  $i$  (Refer to Section 2 for more details).

## 2.2. Experiments

Five fresh frozen cadaveric specimens (average age at death = 71 years) were used. The leg specimen, amputated at the mid-tibia level, was potted in an acrylic plastic tube and mounted on a foot and ankle joint simulator (Fig. 2; MLU). The functionality of the simulator was fully presented elsewhere [15] so that only minimal details were described in this paper as needed. The tendons of six extrinsic muscle groups acting on or around the ankle were loaded: Achilles, tibialis posterior, flexor, extensor, peroneal, and tibialis anterior. A total of six servo-pneumatic cylinders (Fig. 2; SPA 1–6) were used to apply individual tendon loading ( $\Delta f_i$ ) on the specimen. A double-acting servo-pneumatic cylinder (Fig. 2; SPA 0) provided a constant vertical loading on the ankle joint ( $F_j$ ) throughout the entire simulation in the amount of 343 N (35 kg). Before each trial, the foot was positioned such that the 2nd metatarsal and tibia were aligned with the line of progression of the tibia in the sagittal plane. The muscle loading unit (Fig. 2; MLU) could be rotated about the ankle joint using a servo-electric motor (Fig. 2; SEM) so that the tibia was positioned from  $-10^\circ$  (plantarflexion

of the foot and ankle complex) to  $20^\circ$  (dorsiflexion) from the vertical, collecting data at  $5^\circ$  intervals. Each muscle group was loaded at each tibial position with ten cycles of a 49 N (5 kgf) sine wave at 0.02 Hz and the last five cycles were used for measurement to ensure a minimal viscoelasticity effect (Fig. 3). The sole of the foot remained in contact with a custom-made force plate (Fig. 2; MFP) throughout the trial. The initial COP locations ( $p_x$ ) and temporal changes of the COP ( $\Delta p_x^i$ ) during the application of the individual tendon loading were estimated in both A–P and M–L directions. One-way analysis of variance (ANOVA) was conducted to find the effect of the tibial angular position on the DCOP in both directions for each muscle group, using the statistical software SYSTAT 5.04 (SYSTAT, Inc., Evanston, IL), with a level of significance,  $\alpha = 0.05$ .

## 3. Results

Most of the isolated or group of the ankle muscles demonstrated overall linear patterns of the DCOP movement on the transverse plane for the repeated sinusoidal loading (Fig. 4 and Eqs. (6a), (6b) and (6c)),

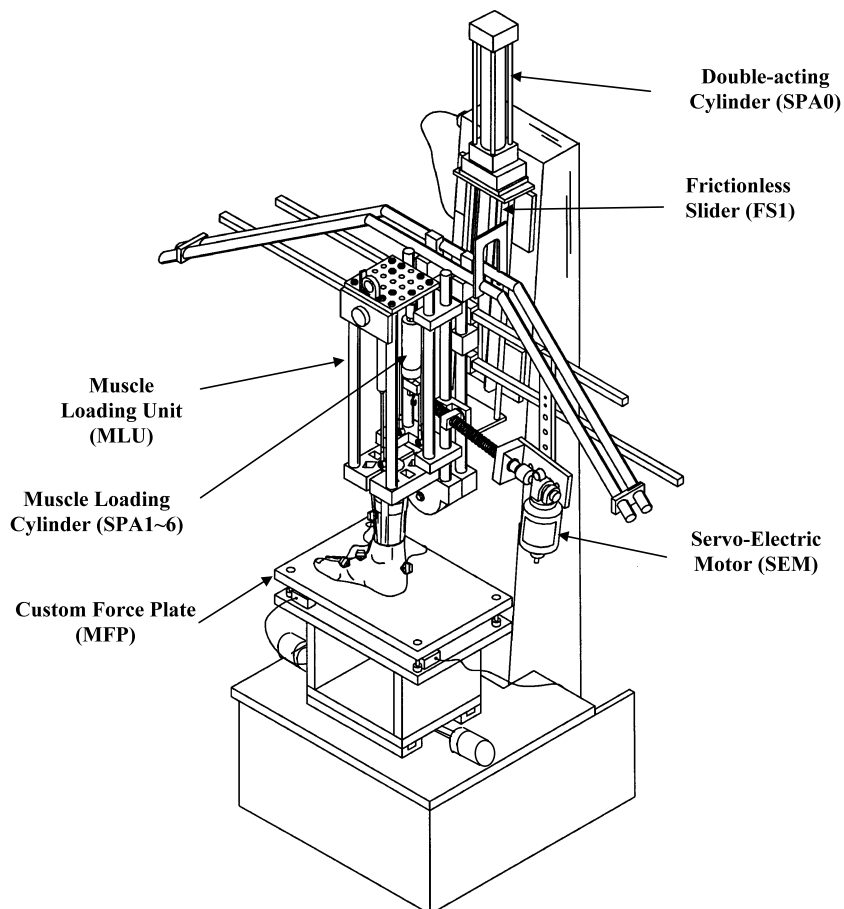


Fig. 2. Experimental setup using a foot and ankle joint simulator ([15], reprinted with permission).

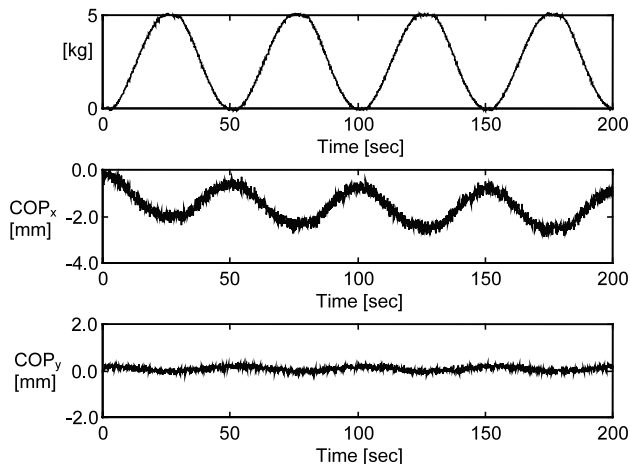


Fig. 3. The DCOP movements for tibialis posterior at 10° dorsiflexion of the foot and ankle complex. A 49 N (5 kg) sinusoidal force was applied on the tendon (Top). The DCOP movements in the A–P (middle) and M–L (Bottom) directions were shown.

with discrepancies between the loading and unloading curves. A sinusoidal loading of 49 N at 0.02 Hz was sufficient to ensure a minimal discrepancy between the two curves and also to avoid heel rise during the simulation. Using Eq. (6c), the moment arms of each group were subsequently estimated for comparisons

with the literature data (Table 1), showing good agreement in general.

Since the flexion angle had statistically significant effects only on the DCOP movement of the flexor group in the A–P direction (ANOVA,  $P = 0.006$ , Fig. 4), the DCOP movements in the A–P and M–L directions were then averaged over the range of the flexion angle for each muscle group and reported in Table 2. Most prominent DCOP movements were noted in the A–P direction, while those in the M–L direction were at most 1.1 mm for 49 N of muscle loading (Table 1; Fig. 4). The calf group had the largest anterior DCOP movement, 6.3 mm for the given muscle loading, while the tibialis posterior muscle had the smallest, 1.3 mm.

Each muscle group demonstrated its unique role of controlling the DCOP movement. The four-quadrant representation of the DCOP movement could simply classify the role of each muscle group (Fig. 4). Only the peroneal group appeared to be responsible for the anterior-medial DCOP movement (the 3rd quadrant), while the calf group could control the DCOP movement in the anterior–lateral direction (the 2nd quadrant). The tibialis anterior muscle was responsible for the posterior–lateral DCOP movement (the 1st quadrant), while the extensor group controlled the DCOP movement in the posterior-medial direction (the 4th quadrant). The

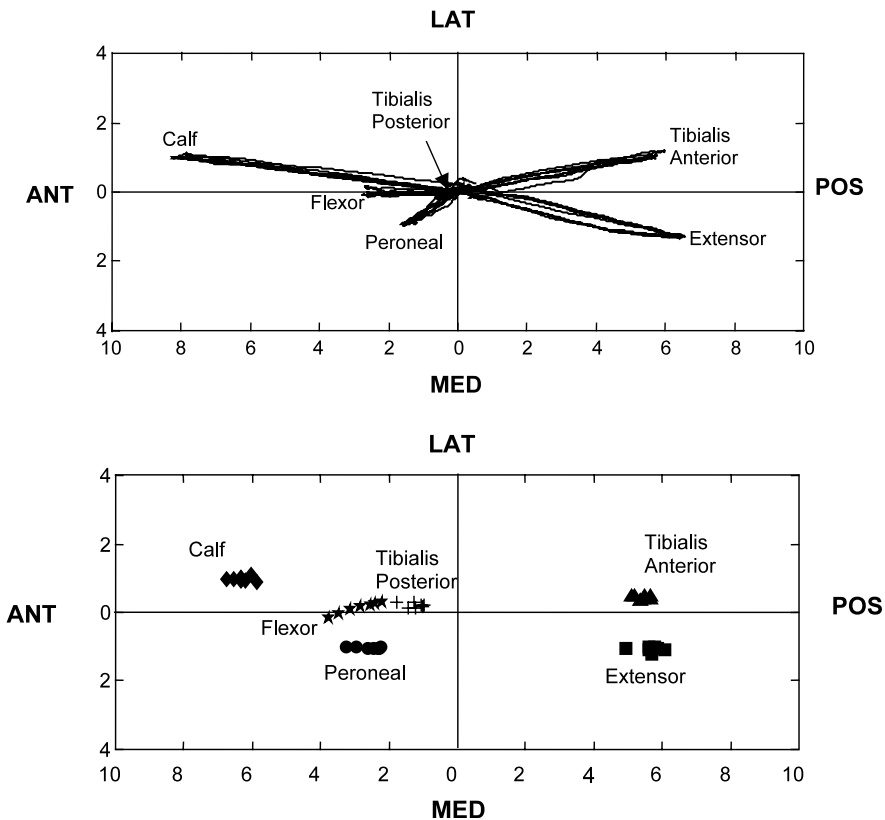


Fig. 4. (Top) The DCOP movements of each muscle group at 0° flexion angle for a sinusoidal muscle force. Note that the DCOP movement of the tibialis posterior muscle (arrow) significantly overlapped with that of the flexor group. (Bottom) The DCOP movements along with the flexion angle between  $-10^\circ$  (plantarflexion of the foot and ankle complex) and  $20^\circ$  (dorsiflexion) at a  $5^\circ$  interval. The units are in millimeter.

Table 1

Estimated moment arms about M–L ( $r_z$ ) and A–P ( $r_x$ ) axes for each isolated or group of the extrinsic ankle muscles

	Peroneal		Extensor	Tibialis anterior	Tibialis posterior	Flexor	Achilles
	Longus	Brevis					
$r_z$	16.4		42.2	38.3	7.0	18.2	44.5
$r_z$ ([17])	12.8	9.9	–	32.0	8.0	26.6 <sup>a</sup>	52.8
$r_z$ (Rugg, 1990) [19]	–	–	–	48.0	–	–	49.0
$r_x$	7.0		7.5	3.2	1.2	1.5	6.7

The units are in millimeter.

<sup>a</sup> For flexor hallucis longus only.

flexor muscle group and tibialis posterior muscle were responsible for the anterior DCOP movement only.

Substantial changes of the DCOP movement along with the flexion angle change were seen only in the flexor muscle group (Fig. 4; about 2 mm anteriorly during 10° plantar- to 20° dorsi-flexion). The DCOP changes for the tibialis anterior muscle and extensor muscle group remained unchanged as the foot and ankle complex became more dorsiflexed, while the rest of the groups showed mostly anterior migration of the DCOP but did not reach the level of significance ( $P > 0.28$ ). The initial COP locations also changed, 9 mm anteriorly and 3 mm laterally over the –10 to 20° flexion angle intervals.

#### 4. Discussion

In this study the DCOP movements of each muscle or muscle group at intervals of flexion angles of the foot and ankle complex were measured using cadaveric specimens through systems identification approach by applying individual tendon loading and constant vertical ankle joint loading with the aid of a foot and ankle joint testing apparatus [15]. This information is crucial to understand the role of each muscle or muscle group in controlling the movement of the COP for postural control. At upright stance (neutral foot position) with a constant vertical ankle joint reaction force and a comparably smaller muscle force, the muscle force and the corresponding vertical GRF play a role of mechan-

ical lever about the ankle joint as a fulcrum (Eqs. (6a), (6b), (6c) and (7)) so that a muscle with a larger moment arm can readily control the COP movement in the opposite direction of the moment arm. Conversely, the current measurement technique can also be used to measure the moment arm of each muscle as shown in Table 1. As noted in Eqs. (6a), (6b) and (6c), the DCOP movement also has an inverse relationship with the vertical ankle joint reaction force or the vertical GRF as long as the muscle force is substantially smaller. However, this relationship becomes nonlinear if the vertical GRF is not comparably bigger than the applied muscle force (Eq. (6a)).

Assuming no mechanical coupling between the muscles, the total COP movement can be expressed as a linear combination of product of the individual DCOP and the ratio of the muscle force to the vertical GRF (Eq. (7)). Thus, the cumulative DCOP movements on the transverse plane will provide two recursive equations in addition to the force and moment equilibrium equations. This results in a decrease of two degrees of freedom in muscle force determination problems. If only two muscles are active, the muscle forces can be uniquely determined using these equations and equilibrium equations. Multiple muscles are working together during postural balance so that, though not sufficient to uniquely determine the individual muscle forces, these two extra pieces of information will constrain the feasible solution space in muscle force determination problems using optimization techniques. Also, this information indicates the physiologic upper bound for

Table 2

Means and standard deviations (in parentheses) of the DCOP movement for six extrinsic ankle muscle groups to sinusoidal loading of 49 N (5 kg) at 0.02 Hz between 10° plantarflexion to 20° dorsiflexion of the foot

	Peroneal	Extensor	Tibialis Anterior	Tibialis Posterior	Flexor	Achilles
$\Delta P_x$	2.63 (0.38)	–5.66 (0.36)	–5.41 (0.22)	1.25 (0.29)	2.89 (0.57)*	6.30 (0.30)
$\Delta P_z$	–1.00 (0.02)	–1.08 (0.08)	0.43 (0.05)	0.20 (0.07)	0.11 (0.17)	0.97 (0.07)

Positive  $\Delta P_x$  indicates the anterior DCOP movement and positive  $\Delta P_z$  is the lateral DCOP movement. The units are in millimeter.\* Denotes statistical significance ( $P < 0.05$ ) of the effect of foot flexion angle from the ANOVA.

muscle force when the whole foot sole is in contact with the ground. For example, the calf muscle group can physiologically generate 7120 N maximally or 10.4 BW (if body mass = 70 kg) [16]. However, the point of application of GRF remains inside the foot ([14]). Assuming the foot is 280 mm and in bipedal balance ( $G_y = 0.5$  BW), the maximum muscle force for calf group will be obtained from Eq. (6c) such that

$$\Delta p_x^i = \frac{r_i}{G_y} \Delta f_i \quad \text{or} \quad 280 = \frac{44.5}{G_y} \Delta f_i \quad (8)$$

$$\therefore \Delta f_i = 3.1 \text{ BW}$$

However, if it is in unipedal balance, the amount is doubled to be 6.2 BW. Therefore, the upper bound of muscle force will be further constrained for physically feasible muscle force solutions.

The distance between the DCOP and the vertical axis (Fig. 4) implies a moment arm for plantar-dorsiflexion as discussed above and from Eq. (6c), while the distance between the DCOP and the horizontal axis indicates a moment arm for inversion–eversion. The calf, tibialis anterior, and extensor muscle groups would have larger moment arms for plantar-dorsiflexion but the tibialis posterior muscle would have the smallest moment arm (Fig. 4; [17]). On the other hand, the peroneal, extensor, and calf groups would have larger moment arms for inversion–eversion [17,2]. Based on these observations, the physical roles of each muscle group can be confirmed from the DCOP plot (Fig. 4; [14]). The four-quadrants imply that the muscle group in the 1st quadrant is responsible for dorsiflexion-inversion, the 2nd quadrant for plantarflexion-inversion, the 3rd quadrant for plantarflexion-eversion, and the 4th quadrant for dorsiflexion-eversion. Our results indicate that the tibialis anterior muscle is a dorsiflexor-invertor, the calf muscle group a plantarflexor-invertor, the peroneal group a plantarflexor-evertor, and the extensor group a dorsiflexor-evertor [16]. The functional role of the flexor group and tibialis posterior muscle appeared to be the similar as a plantarflexor-invertor but a weak invertor, since their DCOP loci were located on the A–P axis (Fig. 4). This observation may serve as a clinical basis of treating posterior tibialis tendon dysfunction through flexor digitorum longus tendon transfer [18].

To assess the mechanical efficiency of each muscle group in controlling the COP movement, physiologic cross-section area (PCSA) of each muscle group can be taken into account by multiplying the DCOP of each muscle group with its PCSA. Most muscle groups have their PCSA's, ranging from 11 to 19 cm<sup>2</sup>, except the calf group having the greatest value of 102 cm<sup>2</sup> [16]. Therefore, Fig. 4 can roughly represent the neuromuscular efficiency of each muscle group by excluding the calf group, having a fivefold magnitude of the product of DCOP and PCSA from the rest. The calf group is the

most efficient COP controller in the anterior direction, while the tibialis anterior muscle and extensor groups are the major COP controllers in the posterior direction. Again, the calf group is a major COP controller in the lateral direction, while the peroneal and extensor groups play a similar role in the medial direction.

Caution should be taken to use the data due to the following limitations of the current in vitro study. The extrinsic ankle muscles were grouped into six functional-equivalents, and the amount of the applied muscle loading was 5 kg. Our pilot observation indicated that the ground contact of the foot sole could be lost for some muscle groups beyond that amount of muscle loading so that simultaneous kinematic measurements would be required. Despite the functional capability of the experimental apparatus for applying full-scale weight loading on the specimen, a reduced amount of weight loading was applied for the old cadaveric specimens to avoid possible structural damages during the repeated measurements. Therefore, the current study may be interpreted as simulation of a bipedal stance with a small amount of postural sway (quiet standing) and may be readily validated through in vivo experiments with similar assumptions used in Section 2. One way is that for a subject in bipedal stance on a set of force plate, individual muscle is stimulated at different activation levels to record the change of the GRF and the concomitant movement of the COP. Other way might be simultaneous measurement of the COP movement and surface electromyography during quiet standing. This is beyond the scope of this study. In our study, the position of the foot and ankle complex was considered in the sagittal plane only, while 3-D positions of the foot and ankle complex, for example, standing sideway on an inclined slope, may have different effects on the DCOP measurement. This study, however, is a first progressive attempt to correlate the individual DCOP movements with the neuromuscular parameters and to facilitate better understanding on foot and ankle biomechanics.

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