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Relationships of three arch height indices related to different foot lengths between sitting and standing postures

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ABSTRACT

Arch height index (AHI) between sitting and standing is an important reference in assessing foot mobility and foot classification in podiatry clinic. The relationships of three types of AHIs related to different foot lengths in sitting and standing postures are desired to be investigated in clinical applications. The purpose of this study is to investigate the relationships of three arch height indices (AHIs) calculated from total foot length, medial ball length and lateral ball length between sitting and standing postures and to examine the performances of them. Three AHIs of right feet of 150 subjects, including 83 males and 67 females, were measured using 3D foot scanner with an accuracy level of 0.05 cm in sitting and standing postures in this study. The results showed that three AHIs were significantly different from each other, and had the same performances between sitting and standing postures. AHI values in the sitting posture were all larger than those in the standing posture, and AHI-MBL has a better explaining power on AHI-TFL than AHI-LBL on AHI-TFL in both postures. The time and priority of using these three AHIs in evaluating foot types with normality and deformity were suggested.

Keywords: Arch height index (AHI), 3D foot scanner, Foot mobility, Sitting, Standing.

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1. INTRODUCTION

Arch height index (AHI) between sitting and standing is an important reference in assessing foot mobility and foot classification in clinic of podiatry (Cowan et al., 1993; Yen et al., 1998; Kaufman et al., 1999; Williams et al., 2001; Lees et al., 2005; Franettovich et al., 2007; Xiong et al., 2010; Kramer and Lautzenheiser, 2022). AHI is usually defined as the dorsal arch height normalized to the total foot length (TFL), that is, the height of the medial longitudinal arch normalized by the total foot length (called AHI-TFL). This definition is appropriate for the normal foot, but not for the foot with deformity, such as hallux valgus, tailor's bunion or claw toe. In a deformed foot, the TFL of the foot is usually affected by the deformity, and the AHI value will then be different. To reduce the effect of the foot deformity on AHI, researchers used the truncated foot length instead of the TFL to calculate AHI (Williams and McClay, 2000, McPoil et al., 2008b). The truncated foot length is measured as the length from the heel to the medial ball point, that is, the medial ball length (MBL). AHI calculated from MBL is also called AHI-MBL. It has been reported that AHI-MBL is more reliable than AHI-TFL in deformed foot (Williams and McClay, 2000). Another advantage of AHI-MBL instead of AHI-TFL is the easy identification of medial ball point of foot, which could reduce the error of measurement of AHI-MBL. However, the disadvantage lies on, in gait analysis, the biomechanical characteristics of medial ball point. The medial ball point is a key point for body weight transmission during exercise. During prolonged lower limb movement, the distance between medial ball point and the heel point could easily be changed, which consequently affects the value of AHI-MBL. Such a phenomenon can often be observed in the foot shape of athletes (Krauss et al., 2010; Arnold and Bishop, 2013). On the other hand, in gait analysis, it is the lateral ball point that is somewhat less likely to be affected by prolonged lower limb movement. Measurement related to the lateral ball point is lateral ball length (LBL), which is the distance between lateral ball point to the heel point. Considering the advantages of both less effect by prolonged lower limb movement and easy identification of foot shape correspondingly, another alternative index of AHI-TFL could be AHI calculated from lateral ball length, called AHI-LBL; however, this index is less studied and discussed. Therefore, there is a desire to investigate the relationships of these three kinds of AHI in sitting and standing postures in clinical applications.

Researchers had measured AHI using different methods, such as callipers method, photography, or radiography. The data from these methods usually had the issue of intra- and inter-rater reliabilities with different degree of rater intervention in process, and their strength was then limited. In addition, the time consumption of these methods or the invasiveness of measurement also limits their applications by clinicians in different clinical sites and the possibility of conducting measurement of large-scaled database. These issues should only be solved only if an AHI measurement system could be adopted, as McPoil et al. (2008a) had concluded: “Future research should focus on developing a method to obtain the arch height difference that can be done easily and quickly in the clinic”. With the advent of 3D foot scanning technology, AHI could now be measured with least amount of rater intervention in the AHI measurement. It could measure the 3D foot form and extract the foot measurement easily and quickly, usually in a few seconds for one foot. With the cost available nowadays, usually in \$1000 - \$10000 USD, 3D foot scanners had recently been applied in establishing 3D foot database of large scale (Robinette et al., 1999; Houston et al., 2006; Luo et al., 2009; Yu and Tu, 2009; Telfer and Woodburn, 2010; Yu et al., 2010; Kimura et al., 2011; Tu, 2014; Tu et al., 2020).

Weight bearing (WB) conditions on the subject’s foot in a sitting or standing posture were also usually concerned in AHI measurement. When the subject adopted a sitting posture during the measurement process, 10%WB and 0%WB conditions were usually used (Zifchock et al., 2006; Butler et al., 2008; McPoil et al., 2008a; McPoil et al., 2009; Pohl and Farr, 2010; Cornwal and McPoil, 2011; McPoil et al., 2013; Zifchock et al., 2017; Zifchock et al., 2019). In the sitting posture with 10%WB, the subject adopted a natural sitting posture with the measured foot resting on the measurement platform. This was a stable posture for the subject. In the sitting posture with 0%WB, the subject was asked to sit on a chair with their measured foot dangling in the air, and the rater had a platform to place under the foot and then measure it. This posture was relatively unstable compared to the posture with 10%WB. When the subject is in a standing posture, 50%WB and 90%WB on the measured foot have usually been asked to be adopted (Williams and McClay, 2000; Zifchock et al., 2006; Mall et al., 2007; McPoil et al., 2008a; Cobb et al., 2011). In the standing posture with 50%WB, the subject was asked to place their body weight equally on both feet, and in the standing posture with 90%WB, the subject was asked to place 90% of their body weight on the measured foot. For the subject, the standing posture with 50%WB was easier to be achieved and more stable for the AHI measurement. Taking sitting posture with 10% and standing posture with 50% in measurement would be easier for subjects to be achieved and stable in AHI measurement.

The purpose of this study is to investigate the relationships of three AHIs related to different foot lengths between sitting and standing postures.

2. MATERIALS AND METHODS

2.1 Subjects

A total of 150 subjects, including 83 males and 67 females, were recruited to scan their right feet. They were recruited from the college or graduate students and aged in 18 to 24 years old. All subjects had no reported history of foot surgery or trauma. Subjects were included after the informed consent form was obtained. The heights and weights of the male, the female and the total (male and female combined) were listed in Table 1.

Table 1. Heights and weights of the subjects

	Number	Height (cm)		Weight (kg)	
		Mean	S.D.	Mean	S.D.
Total	150	166.84	9.44	61.25	14.03
Male	83	173.41	6.21	68.41	11.45
Female	67	158.70	5.64	52.38	11.73

2.2 Apparatus

A 3D foot scanner developed by Industrial Technology Research Institute (ITRI) in Taiwan was used in this study. It was equipped with four measuring heads and a reinforced optical glass with a size of 450 × 280 × 5 mm, on which the foot stood and was measured. It took about 6 s to complete a scan. A control and analysis software, Anthro3D, was used to control the 3D foot scanner and to analyse the scan data. Its accuracy level had been reported as measurement errors below 0.05 cm in 1D measurements (Yu and Tu, 2009), which is much smaller than 0.2 cm, which in ISO 20685 was considered standard when measuring foot measurements, and were highly acceptable.

2.3 Procedures

The right feet of all subjects were scanned in sitting and standing postures. In sitting posture, the subject was asked to sit on a hydraulically adjustable chair. The height of the chair was adjusted such that his/her knee and ankle joint were at 90 degrees as shown in Fig. 1, and his/her right foot was puts on the optical glass and scanned. It is assumed to have 10%WB on the right foot in the sitting posture

(Dempster and Gaughran, 1967; Zifchock et al., 2006). In standing posture, the subject was asked to assume a standing posture with equally weight bearing (50%WB) on both feet as shown in Fig. 2. The subject's right foot was on the optical glass to be scanned, and the left foot on the platform aside the 3D foot scanner, whose height is the same as the one of the optical glass.

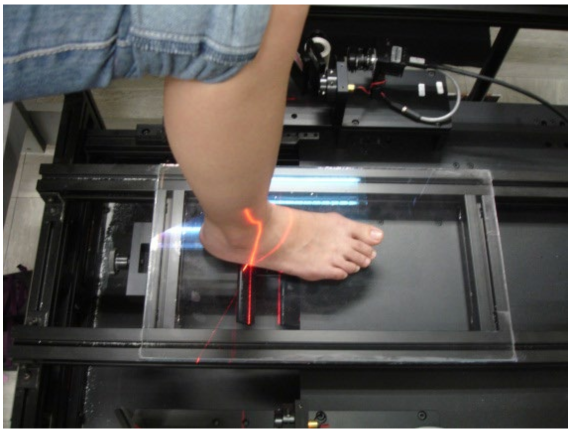
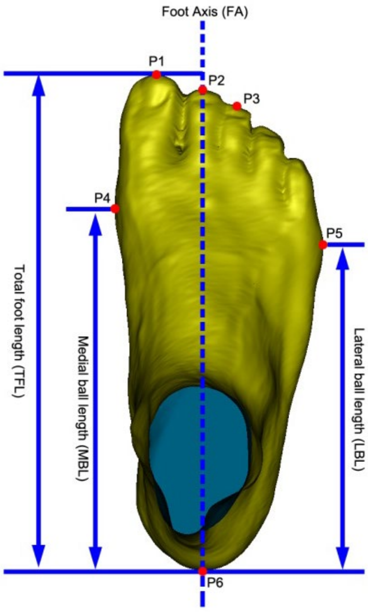


Fig. 1. The subject's right foot scanned when his/her knee and ankle joint were at 90 degrees

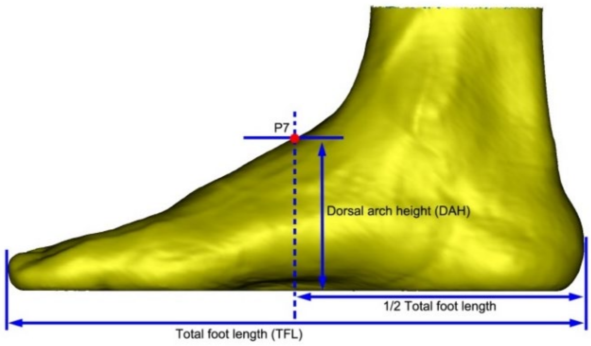
Fig. 2. The subject's right foot was scanned when he/she was asked to assume a standing posture with equally weight bearing (50%WB) on both feet

2.4 Foot Measurement Items

Four measurements in sitting and standing postures were extracted from the foot scan by the Anthro3D software automatically, including TFL, MBL, LBL, and dorsal arch height. Seven foot landmarks were identified before extracting these four measurements, including 1st toe tip (P1), 2nd toe tip (P2), 3rd toe tip (P3), medial ball point (P4), lateral ball point (P5), the heel point (P6), and dorsal arch height point (P7), as illustrated in Fig. 3. The line passing through the heel point and the tip of 2nd toe was called foot axis (FA), which was the basic reference for lengths on foot. The TFL was the distance between the heel point and the tip of the longest toe (as 1st toe tip in Fig. 3 (a)) and parallel to FA. The MBL was the distance between heel point and medial ball point and parallel to FA, and the LBL was the distance between heel point and lateral ball point and parallel to FA. Arch height was the vertical distance between dorsal arch height point and the plane on which the foot stands was dorsal arch height, as shown in Fig. 3 (b). Three AHIs in this study would be defined as arch height divided by TFL, arch height divided by MBL, and arch height divided by LBL respectively.



(a)



(b)

Fig. 3. Foot measurements and landmarks in this study: four measurements are TFL, MBL, LBL, and arch height; Seven landmarks include 1st toe tip (P1), 2nd toe tip (P2), 3rd toe tip (P3), medial ball point (P4), lateral ball point (P5), the heel point (P6), and dorsal arch height point (P7)

2.5 Data Analysis

Four measurements between sitting and standing were tabulated in total, male and female populations, and analyzed by Student T-test on gender. From these measurements, three AHIs in sitting and standing postures were calculated, including AHI calculated with total foot length (AHI-TFL), AHI calculated with medial ball length (AHI-MBL) and AHI calculated with lateral ball length

(AHI-LBL). At first, each of three AHIs in sitting and standing postures were analyzed by Student T-tests on genders to know if there were differences or not for each AHI between genders. If there were significant differences of each AHI between genders, the further analyses should be gender-specific; if not, the male population and the female population could be taken as a whole population in each AHI, and the further analyses could be focused on this whole population. Each of three AHIs in sitting and standing postures were then analyzed by paired Student T-test on postures to see if there were differences or not between postures. If postures affected AHI significantly, the differences of each AHI would then be shown. After analysis with respect to sitting and standing postures, three AHIs were also analyzed by paired Student T-test on each other to see if there were differences or not among three AHIs. Finally, AHI-MBL and AHI-LBL would be regressed on AHI-TFL respectively to see their relationships.

3. RESULTS

The result of four measurements between sitting and standing was tabulated in total, male and female population, as shown in Table 2. In sitting posture of total population, foot length had a mean of 243.66 mm with a standard deviation (S.D.) of 17.07 mm, ranging in 202.29 to 277.31 mm. MBL had a mean of 178.39 mm with a S.D. of 13.19 mm, ranging in 146.10 to 206.17 mm. Lateral ball length had a mean of 156.89 mm with a S.D. of 11.72 mm, ranging in 128.19 to 179.95 mm. Dorsal arch height had a mean of 67.64 mm with a S.D. of 5.68 mm, ranging in 52.71 to 81.37 mm. In standing posture of total population, foot length had a mean of 247.38 mm with a S.D. of 16.95 mm, ranging in 205.95 to 278.87 mm. MBL had a mean of 181.15 mm with a S.D. of 13.11 mm, ranging in 147.15 to 207.13 mm. Lateral ball length had a mean of 157.82 mm with a S.D. of 11.78 mm, ranging in 130.16 to 180.12 mm. Dorsal arch height had a mean of 62.74 mm with a S.D. of 5.54 mm, ranging in 46.61 to 75.34 mm. The results of these four measurements analyzed by Student T-test with respect to male and female were shown in Table 3. All p values were less than 0.001 with $\alpha = 0.05$. There were significant differences of these four measurements between genders.

The results of each AHIs in sitting and standing postures analyzed with respect to gender by Student T-test were shown in Table 4. All p values were larger than 0.05 with $\alpha = 0.05$. The result showed that there were no significant differences of each AHI between genders, and the male population and the female population could be taken as a whole population in each AHI in further analyses.

The results of each AHIs analyzed with respect to postures by paired Student T-test were shown in Table 5. All p values were less than 0.001 with $\alpha = 0.05$. The results showed that there were significant difference of each AHI between sitting and standing postures, and AHI values in sitting posture were larger than ones in standing posture. The differences of AHIs between sitting and standing postures were 0.024 as mean and 0.008 as S.D. in AHI-TFL, 0.033 as mean and 0.012 as S.D. in AHI-MBL, and 0.034 as mean and 0.012 as S.D. in AHI-LBL.

The results of three AHIs analyzed by paired Student T-test on each other were shown in Table 6. All p values were less than 0.001 with $\alpha = 0.05$ in both sitting and standing postures. The results showed that there are significant differences among these three AHIs on each other.

The regression models of AHI-MBL on AHI-TFL and of AHI-LBL on AHI-TFL in sitting and standing postures were shown in Table 7. In sitting posture, the model of AHI-MBL on AHI-TFL has $R^2 = 0.952$, and the model of AHI-LBL on AHI-TFL has $R^2 = 0.841$. In standing posture, the model of AHI-MBL on AHI-TFL has $R^2 = 0.936$, and the model of AHI-LBL on AHI-TFL has $R^2 = 0.850$.

Table 2. Four measurements in sitting and standing postures in total, male and female populations (Units: mm)

Population	Posture					
	Sitting			Standing		
	Mean	S.D.	Range	Mean	S.D.	Range
(a) Total						
TFL	243.66	17.07	202.29–277.31	247.38	16.95	205.95–278.87
MBL	178.39	13.19	146.10–206.17	181.15	13.11	147.15–207.13
LBL	156.89	11.72	128.19–179.95	157.82	11.78	130.16–180.12
Dorsal arch height	67.64	5.68	52.713–81.37	62.74	5.54	46.61–75.34
(b) Male						
TFL	255.72	11.30	232.40–277.31	259.32	10.91	278.87–236.75
MBL	187.87	8.42	169.72–206.17	190.63	7.89	207.13–174.41
LBL	164.87	7.63	148.15–179.95	165.89	7.74	180.12–147.14
Dorsal arch height	70.76	4.32	62.58–81.37	65.79	4.38	75.34–57.27
(c) Female						
TFL	228.71	9.55	202.29–245.85	232.59	10.03	250.73–205.95
MBL	166.65	7.48	146.10–183.41	169.39	7.81	186.00–147.15
LBL	147.02	7.75	128.19–163.97	147.82	7.44	163.99–130.16
Dorsal arch height	63.77	4.59	52.71–75.41	58.97	4.28	71.38–46.61

Table 3. Four measurements in sitting and standing postures analyzed by student t-test on genders (Unit: mm)

Measurement	Posture	Gender				t value	p value
		Male		Female			
		Mean	S.D.	Mean	S.D.		
TFL	Sitting	255.72	11.25	228.71	9.55	15.62	< 0.001
	Standing	259.32	10.88	232.59	10.03	15.49	< 0.001
MBL	Sitting	187.87	8.23	166.65	7.48	16.35	< 0.001
	Standing	190.63	7.70	169.39	7.81	16.68	< 0.001
LBL	Sitting	164.87	7.57	147.02	7.75	14.21	< 0.001
	Standing	165.89	7.74	147.82	7.44	14.47	< 0.001
Dorsal arch height	Sitting	70.76	4.43	63.78	4.59	9.44	< 0.001
	Standing	65.79	4.48	58.97	4.28	9.45	< 0.001

Table 4. AHIs in sitting and standing postures analyzed with respect to gender by student t-test

AHIs	Posture	Gender				t value	p value
		Male		Female			
		Mean	S.D.	Mean	S.D.		
AHI-TFL	Sitting	0.277	0.021	0.279	0.016	-0.510	0.305
	Standing	0.254	0.020	0.254	0.016	0.180	0.429
AHI-MBL	Sitting	0.377	0.028	0.383	0.0240	-1.306	0.097
	Standing	0.346	0.026	0.348	0.023	-0.667	0.253
AHI-LBL	Sitting	0.430	0.032	0.434	0.025	-0.836	0.202
	Standing	0.397	0.031	0.399	0.025	-0.415	0.339

Table 5. AHIs analyzed with respect to postures by paired student t-test

AHIs	Posture				t value	p value	Difference between sitting and standing postures	
	Sitting		Standing					
	Mean	S.D.	Mean	S.D.			Mean	S.D.
AHI-TFL	0.278	0.019	0.254	0.0179	-36.013	< 0.001	0.024	0.008
AHI-MBL	0.380	0.026	0.347	0.0248	-33.893	< 0.001	0.033	0.012
AHI-LBL	0.432	0.029	0.398	0.0281	-34.648	< 0.001	0.034	0.012

Table 6. Three AHIs analyzed with respect to each other by paired student t-test

Posture	AHIs						AHI-TFL vs. AHI-MBL		AHI-MBL vs. AHI-LBL		AHI-TFL vs. AHI-LBL	
	AHI-TFL		AHI-MBL		AHI-LBL							
	Mean	S.D.	Mean	S.D.	Mean	S.D.	t value	p value	t value	p value	t value	p value
Sitting	0.278	0.019	0.380	0.026	0.432	0.029	-139.363	< 0.001	-55.843	< 0.001	-137.324	< 0.001
Standing	0.254	0.018	0.347	0.025	0.398	0.028	-136.906	< 0.001	-57.166	< 0.001	-129.385	< 0.001

The results showed that both AHI-MBL and AHI-LBL had good explaining power on the variance of AHI-TFL in both sitting and standing postures, and the AHI-MBL has better power on AHI-TFL than that of AHI-LBL on AHI-TFL.

Table 7. Regression models of AHI-MBL and AHI-LBL on AHI-TFL

Posture	Regress model	R^2
Sitting	AHI-TFL = 0.008 + 0.710 × AHI-MBL	0.936
	AHI-TFL = 0.017 + 0.604 × AHI-LBL	0.850
Standing	AHI-TFL = 0.010 + 0.704 × AHI-MBL	0.952
	AHI-TFL = 0.021 + 0.585 × AHI-LBL	0.841

4. DISCUSSION

3D foot scanner with Anthro3D software used in this study is easier and quicker to be used in measuring AHI between sitting and standing postures with accuracy. It is easier than the previous methods for no need of rater's intervention in measurement. There would be no the issue of intra- and inter-rater reliabilities. Without rater's intervention, the beforehand requisitions of rater's training to palpate or identify the foot landmarks could be reduced. Consequently, it reduces the measuring time. The measuring time consists of manipulation of rater's intervention and the measuring time of device. The 3D foot scanner could measure and identify one foot in less than 6 s with 0.05 cm as accuracy level. These advantages make the 3D foot scanner a good alternative system to measure AHI and to establish a large-scaled AHI database.

Each of three AHIs (AHI-TFL, AHI-MBL, AHI-LBL) had significant difference between sitting and standing postures, but no significant difference between genders.

With comparison of dorsal arch height alone which showed significant difference between genders (see also Table 3), AHI is a more robust index to evaluate the change of medial longitudinal arch of subjects between sitting and standing postures. This study had provided three AHI values as reference for Taiwanese people.

All regression models of AHI-MBL on AHI-TFL and AHI-LBL on AHI-TFL in sitting and standing postures had $R^2 > 0.84$. It shows that AHI-MBL and AHI-LBL both had good explaining power on the variance of AHI-TFL in both sitting and standing postures. Between AHI-MBL and AHI-LBL, regression model of AHI-MBL on AHI-TFL had higher R^2 than the one of AHI-LBL on AHI-TFL. It might result from the fact that the geometric characteristics of 1st metatarsal-phalangeal joint (its protrusion) is easier to be identified than that of 5th metatarsal-phalangeal joint from 3D foot forms by computer algorithm. From the results of regression, the time and priority of using these three AHIs to evaluate the medial longitudinal arch of 3D foot forms could be suggested as follows: for normal foot, three AHIs could all be used with the priority of AHI-TFL, AHI-MBL and AHI-LBL; for foot with deformity, AHI-MBL and AHI-LBL could be used with the priority of AHI-MBL and AHI-LBL.

Resultant AHI-MBLs in this study are consistent with those in the previous studies, in which AHI-MBL was shown as AHI with truncated foot length). For AHI-MBL with subjects in sitting posture (10%WB), there is no significant difference with ours and those in the previous studies, that is, Cobb et al. (2011), Pohl and Farr (2010) and William and McClay (2000), as shown in Table 8 with t-test. For AHI-MBL with subjects in standing posture (50%WB), our results are also of no significant difference with the previous studies, that is, Pohl and Farr (2010) and McPoil et al. (2008b), as shown in Table 9 with t-test. Such consistency showed partially that 3D scanning system as that adopted in this study is practicable for measuring AHIs in sitting and standing postures. Further studies are needed for discussing the ethnic effect on AHI.

The strength of this study is to provide the pilot database of AHI-TFL, AHI-MBL, AHI-LBL, and the relationships among these three indices in terms of regression models. Such information are important as references for ergonomists in designing foot-related products, such as shoes or prosthetics, and for physical therapists in assessing or evaluating postoperative treatment on patient's foot. The weakness of this study is the small number of subjects recruited, which limits the strength of it. In addition, ethnicity issue is not discussed in this study.

5. CONCLUSION

Three AHIs (AHI-TFL, AHI-MBL and AHI-LBL) of right feet of 150 subjects, including 83 males and 67 females, were measured by 3D foot scanner in sitting and standing postures in this study. The results showed that three AHIs were significantly different from each other between sitting and standing postures. AHI values in sitting posture were all larger than the ones in standing posture, and AHI-MBL has better explaining power than AHI-LBL on AHI-TFL in both postures. The time and priority of using these three AHIs in evaluating foot with normality and deformity were suggested.

Table 8. Comparison of AHI-MBLs of sitting posture in this study and previous studies

Research	Mean	S.D.	N	t-value	p-value
This study	0.380	0.026	150	-	-
Cobb et al. (2011)	0.383	0.027	111	1.367	0.086
Pohl and Farr (2010)	0.375	0.020	20	0.827	0.205
William and McClay (2000)	0.300	0.600	102	1.632	0.052

Table 9. Comparison of AHI-MBLs of standing posture in this study and previous studies

Research	Mean	S.D.	N	t-value	p-value
This study	0.347	0.025	150	-	-
Pohl and Farr (2010)	0.345	0.025	20	0.336	0.369
McPoil et al. (2008b)	0.345	0.030	850	0.771	0.221

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