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Foot volume estimation formula in healthy adults

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ABSTRACT

Foot volume (FV) is an important measurement in clinics or industrial applications. Direct measurement and anthropometric formula were methods usually used to evaluate FV. However, direct measurement is usually cumbersome for patients. Three anthropometric formulas were proposed to estimate FV, including wedge method, prism method, and figure-of-eight linear regression model, but none of them could estimate FV with good accuracy and ease of use. The purpose of this study is to derive a formula to estimate FV easily and accurately. 3-D foot forms of the right feet of 122 males and 96 females were scanned with good accuracy. FV and nine 1-D foot measurements were extracted from these 3-D foot scans. From these foot scans, a new FV estimation formula based on foot length, ball girth, and instep girth was derived with R^2 as 0.973. It is of simple and geometrically meaningful form, and is easier to be applied in clinics or industrial applications with accuracy.

Relevance to industry: Foot Volume (FV) is an important measurement in clinics or industrial applications. This study had provided a simple FV estimation formula with R^2 as 0.973 by three 1-D foot measurements.

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Practitioner summary

The purpose of this study is to derive a formula to estimate FV easily and accurately. 3-D foot forms of the right feet of 122 males and 96 females were scanned with good accuracy. FV and nine 1-D foot measurements were extracted from these 3-D foot scans. From these foot scans, a new FV estimation formula based on foot length, ball girth, and instep girth was derived with R^2 as 0.973. It is of simple and geometrically meaningful form, and is easier to be applied in clinics or industrial applications with accuracy.

1. Introduction

Foot volume (FV) is an important measurement in clinics or industrial applications, such as to estimate the response or efficacy of treatments in ankle edema, lymphedema, foot swelling (Tierney et al., 1996; Stanton et al., 2000; Hirai et al., 2012), or inner space estimation of shoe making (Rossi and Tennant, 1993; McWhorter et al., 2006; Witana et al., 2006; Branthwaite et al., 2013). Therefore, method to evaluate FV quickly and accurately is required eagerly.

Two kinds of methods were usually used to evaluate FV, one is direct measurement, and the other is anthropometric estimation formula. Water volumetry and optoelectric method are usually used in direct measurement. Water volumetry has been accepted as golden standard for a long time. A foot was placed into a tank full of water. Volume of water flowing out of the tank is the estimated FV. Many researchers had used it to evaluate FV in their studies (Petersen et al., 1999; Brijker et al., 2000; Mohlokar and Fenelon, 2001; McWhorter et al., 2003; Henschke et al., 2006; McWhorter et al., 2006; Friends et al., 2008; Pasley and O'Connor, 2008; Brodovicz et al., 2009; Rabe et al., 2010; da Luz et al., 2013; Mosti and Partsch, 2013). However, the procedure is messy and time consuming, and sometimes, it might be cumbersome or disallowed for patients in post-operative period or with ulcers or open wounds in limbs. Optoelectric method is a kind of 3-D scanning technology (Tierney et al., 1996; Stanton et al., 2000; Cormier et al., 2009; Ward et al., 2009; Czerniec et al., 2010; Engelberger et al., 2011; Tan et al., 2013). It has been taken as new golden standard in measuring volume of limbs by Stanton et al. (2000). They used optoelectric device named Perometer© to measure the circumferential measurements of the limb along to its longitudinal direction, and calculated its volume with accuracy. However, due to the limitation of the technology, Stanton et al. did not recommend measuring FV by Perometer.

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Friends et al. (2008) had tried to measure FV by Perometer. They posed the subject's foot in full ankle plantarflexion posture, so that the foot could be taken as a truncated cone along to the longitudinal direction of shank and measured. They reported this method with R^2 equal to 0.81 with some measurement issues. With the advent of the 3-D scanning technology, 3-D foot form could now be measured with great accuracy, and had been used widely in many foot researches (Witana et al., 2006; Hu et al., 2007; Xiong et al., 2008; Luo et al., 2009; Park et al., 2009; Xiong et al., 2009; Yu and Tu, 2009; Han et al., 2010; Telfer and Woodburn, 2010; Xiong et al., 2010; Yu et al., 2010; Ma et al., 2011; Lee et al., 2012; Rodrigo et al., 2012; Sims et al., 2012; Telfer et al., 2012). Nevertheless, the procedure is still time consuming, and sometimes cumbersome for patients.

Anthropometric estimation formula is usually used to evaluate FV with ease of use. It uses several 1-D foot measurements to evaluate FV, such as wedge method, prism method, and linear regression model of figure-of-eight method. Wedge method is a FV estimation formula proposed by Jones and Pearson (1969), as shown in Equation (1). In Equation (1), the foot was taken as a wedge in geometry, and the formula of wedge was used to estimate the FV by applying corresponding 1-D foot measurements. These measurements include foot length (FL), diameter of foot ankle girth as a circle (D), and the height of ankle (AGH) in Equation (1). The correlation coefficient between FV estimated by wedge method and FV by water volumetry was reported in the range of 0.83–0.91. In other words, the coefficient of determination (R^2) is in the range of 0.689–0.828 correspondingly. Friends et al. (2008) had proposed another formula named prism method in their study. It is similar with wedge method but the ball breadth (BB) of foot was used instead of the diameter of foot ankle girth, and the height of lateral malleolus (LMH) instead of the height of ankle girth, as shown in Equation (2). The R^2 of prism method was reported as 0.71. R^2s of both wedge method and prism method are not very high, however their forms could benefit for memory and ease to use in clinics. Their forms have only one coefficient in formula, and as the multiplication of three 1-D measurements as estimation of the volume. Without similar form as wedge method, Friends et al. (2008) had also proposed a linear regression model as FV estimation formula in their study, as shown in Equation (3). In this formula, they used one compounded 1-D foot measurement (LinF8) as independent variable. This compounded 1-D foot measurement measured by the figure-of-eight method (Manuela et al., 2007) is by its definition a sum of circumference passing both malleoli and circumference passing navicular point. The R^2 of this formula was reported as high as 0.96. However, the geometric meaning of this formula is not intuitive, and two coefficients in it have to be memorized. This might be the burden for user to apply. In addition, Friends et al. used only data of 10 subjects to derive this formula in regression analyses. The small sample size of the subjects might limit the applicability of this formula.

$$\mathrm{FV} = \frac{1}{2} \times \mathrm{FL} \times D \times \mathrm{AGH} \tag{1}$$

$$\mathrm{FV} = \frac{1}{2} \times \mathrm{FL} \times \mathrm{BB} \times \mathrm{LMH} \tag{2}$$

$$\mathrm{FV} = 35.616 \times \mathrm{LinF8} - 1108.6 \tag{3}$$

Considering there is still no anthropometric formula for FV estimation with accuracy and ease of use, the purpose of this study is to derive a FV estimation formula from the 3D foot forms, by which the FV could be estimated easily and accurately. This formula should have R^2 higher than 0.95 and would be in the form similar with that of wedge method.

2. Method

2.1. Subjects

122 males and 96 females were recruited to scan their right feet in this study. They are aged in 18–24 years old. All subjects had no reported history of foot surgery, trauma, or deformity. Subjects were scanned and included after the informed consent form in accordance with Declaration of Helsinki was obtained. The heights and weights of the subjects as male, female, and total population (male and female combined) are shown in Table 1.

2.2. The apparatus

2.2.1. 3-D foot scanner

A 3-D 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, TriD, was used to control the 3-D foot scanner and analyze the scan data.

2.2.2. Computation software of FV and 1-D foot measurements

The result of the foot scan was used to compute FV and to extract nine 1-D foot measurements using TriD software. The FV is defined as the whole foot volume below the level of the ankle girth. The FV measurement is calculated by summing up all the signed volume of tetrahedrons forming the whole foot volume of 3D foot scan. Each tetrahedron is formed by four vertices, including three vertices of each triangular mesh on 3D foot scan and another point out of the same mesh. The signed volume of it can then be calculated by matrix algorithm as Equation (4), where the coordinates of point V_i is (x_i, y_i, z_i) in Euclidean space of 3D foot scan, V_0 is one arbitrary point out of the convex hull of 3D foot scan, and V_1, V_2, V_3 are three vertices of any triangular mesh of the 3D foot scan (Schneider and Eberly, 2003). Nine 1-D foot measurements were extracted based on the definitions as described in Web Association (1978), Jones and Pearson (1969), and Friends et al. (2008), and are illustrated in Fig. 1. These nine 1-D foot measurements included foot length (FL), ball girth (BG), ball breadth (BB), instep girth (IG), instep height (IH), ankle girth (AG), height of ankle girth (AGH), height of lateral malleolus (LMH), and length in figure-of-eight-method (LinF8). It should be noted that LinF8 is calculated by summation of two circumferences, one is the circumference of the cross section passing both the lateral and the medial malleolus points, and the other is the circumference of the cross section passing the anterior point of the first circumference and perpendicular to the plane (see Fig. 2). It is an approximation of length in figure-of-eight-method in Manuela et al. (2007) because of the difficulty of identifying navicular point from 3D foot scan, which is of no obvious geometric characteristics and is usually identified by manual palpation in clinics. To extract these nine 1-D foot measurements, nine foot landmarks were identified automatically, including 1st toe tip, 2nd toe tip, 3rd toe tip, medial ball point, lateral ball point, instep point, heel point, medial malleolus point, lateral malleolus point.

Table 1
Data of subjects' heights and weights.

	Height (cm)		Weight (kg)	
	Mean (S.D.)	Range	Mean (S.D.)	Range
Male	169.07(6.63)	185.5–155	66.31(13.48)	103.5–45
Female	156.74(6.82)	176–141	52.27(11.72)	88–34
Total	163.36(9.1)	185.5–141	59.81(14.48)	103.5–34

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