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Spatial resolution in plantar pressure measurement revisited

Todd C. Pataky *

Department of Bioengineering, Shinshu University, Japan

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ABSTRACT

Plantar pressures are typically measured using sensors of finite area, so the accuracy with which one can measure true maximum pressure is dependent on sensor size. Measurement accuracy has been modeled previously for one patient's metatarsals (Lord, 1997), but has not been modeled either for general subjects or for other parts of the foot. The purposes of this study were (i) to determine whether Lord's (1997) model is also valid for heel and hallux pressures, and (ii) to examine how sensor size relates to measurement accuracy in the context of four factors common to many measurement settings: pressure pulse size, foot positioning, pressure change quantification, and gross pressure redistribution. Lord's (1997) model was first generalized and was then validated using 10 healthy walking subjects, with relatively low RMSE values on the order of 20 kPa. Next, postural data were used to show that gross pressure redistributions can be accurately quantified ($p < 0.002$), even with rather gross sensor sizes of 30 mm. Finally, numerical analyses revealed that the relation between sensor size and measurement accuracy is highly complex, with deep dependency on the measurement context. In particular, the critical sensor widths required to achieve 90% accuracy ranged from 1.7 mm to 17.4 mm amongst the presently investigated scenarios. Since measurement accuracy varies so extensively with so many factors, the current results cannot yield specific recommendations regarding spatial resolution. It is concluded simply that no particular spatial resolution can yield a constant measurement accuracy across common plantar pressure measurement tasks.

1. Introduction

To accurately characterize local plantar pressure maxima, it has been proposed that spatial resolution should be no coarser than 6.2 mm (Davis et al., 1996), and current international guidelines recommend 5 mm (Giacomozzi, 2011). These recommendations are supported by analytical modeling (Lord, 1997), which shows that a 5 mm resolution can quantify local metatarsal pressure maxima with an accuracy of 90%, but that a 10 mm resolution causes a 30% underestimation.

These studies address spatial resolution from the perspective of measuring relatively high-frequency local maxima in pathological feet, representing an important clinical use of plantar pressure measurement devices. However, Davis's (1996) results show that much lower spatial frequencies dominate the power spectrum, and the general literature shows that a study's focus may not be on single high-frequency pulses. Examples include those which focus on the heel (Nicosia et al., 2007), which is spatially broader than other foot structures, those which focus on *changes* in local maxima, for example: following orthotic intervention (Spencer, 2000), and those which focus on whole-foot distribution patterns (De Cock et al., 2005). If different plantar pressure phenomena indeed have different spatial frequencies, then from the Nyquist–Shannon sampling theorem (Shannon, 1949) it follows that a specific device will measure different phenomena with different accuracies.

In tandem with spatial resolution is sensor positioning. As previously emphasized, although not explicitly analyzed: "the placement of an individual (sensor) is critical to the reliability of the results" (Lord, 1997, p. 144). Since the foot can adopt an arbitrary posture on a pressure measurement device, sensor positioning is also clearly important to consider.

The purposes of this study were (i) to determine whether a generalized form of Lord's (1997) metatarsal model is also valid for non-pathological feet and for other parts of the foot, and (ii) to examine how spatial resolution relates to measurement accuracy in the context of the four aforementioned factors, which are common to many plantar pressure measurement scenarios, but which have not been explicitly analyzed. Specifically, the four factors were pressure pulse wavelength, changes in local pressure maxima, sensor positioning, and gross pressure redistribution. It is noted that this is not an exhaustive list, and also that current focus, like Lord (1997), is predominantly on the ideal sensor grid.

* Tel.: +81 0268 21 5609.
E-mail address: tpataky@shinshu-u.ac.jp

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2. Methods

2.1. Pressure pulse model

Lord's (1997) symmetrical cosine pulse model of the metatarsal heads (p. 142) can be generalized to a 2D asymmetrical pulse of arbitrary size (Fig. 1) as

$$f(x,y)=\frac{F}{\lambda_x\lambda_y}\left(1+\cos\left(\frac{2\pi}{\lambda_x}x\right)\right)\left(1+\cos\left(\frac{2\pi}{\lambda_y}y\right)\right)\mathbf{1}_{\{|x|\le(1/2)\lambda_x\}}\mathbf{1}_{\{|y|\le(1/2)\lambda_y\}} \tag{1}$$

where all symbols are described in Table 1, and where $\mathbf{1}$ is the indicator function, specifying that $|x|$ and $|y|$ larger than $\frac{1}{2}\lambda_x$ and $\frac{1}{2}\lambda_y$, respectively, yield $f(x,y)=0$. A total force (Appendix A) of F=100 N and wavelengths of $\lambda_x=\lambda_y=20$ mm reproduce Lord's original model (Appendix B). The local maximum pressure (p^*) is found at $(x,y)=(0,0)$:

$$p^*=\frac{4F}{\lambda_x\lambda_y} \tag{2}$$

In reality, p^* cannot be directly measured because pressure must be measured over a finite area, and infinitely small pressure sensors do not exist. In addition to, and separate from the pulse model, a measurement model is thus needed to assess p^* measurement accuracy.

2.2. Pressure measurement model

Following Lord (1997), the present measurement model considers only the simplest case of the ideal sensor grid (Fig. 2), on which a square sensor of width w and centered at (x_0,y_0) yields a measured pressure ($\hat{p}$) of

$$\hat{p}=\frac{1}{w^2}\int_{x_0-w/2}^{x_0+w/2}\int_{y_0-w/2}^{y_0+w/2} f(x,y)\,\mathrm{d}x\,\mathrm{d}y \tag{3}$$

Width w is used to specify sensor geometry throughout to be consistent with the units (mm) of international resolution recommendations (Giacomozzi, 2011). If a sensor is centered (x_0=y_0=0) on the aforementioned pulse model Eq. (1), then the solution to Eq. (3) is

$$\hat{p}=\frac{F}{\lambda_x\lambda_y}\left(1+\frac{\lambda_x}{w\pi}\sin\left(\frac{w\pi}{\lambda_x}\right)\right)\left(1+\frac{\lambda_y}{w\pi}\sin\left(\frac{w\pi}{\lambda_y}\right)\right) \tag{4}$$

As above, the values of F=100 N and $\lambda_x=\lambda_y=20$ mm reproduce Eq. (2) from Lord (1997), with a minor exception (Appendix C). An analytic solution for a non-centered sensor is also derivable (Appendix D) and is used in subsequent analyses. Following Lord (1997), measurement accuracy is presently defined as the ratio between the measured ($\hat{p}$) and true maximal pressure (p^*):

$$\hat{p}\text{ accuracy}\equiv\frac{\hat{p}}{p^*}\times 100\% \tag{5}$$

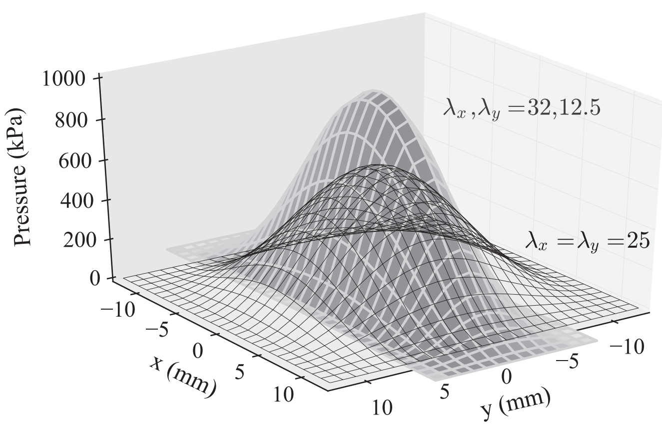

Fig. 1. Pressure model Eq. (1). Depicted are a symmetrical pulse with a wavelength of $\lambda=25$ mm, an asymmetrical pulse with $\lambda_x=32$ mm and $\lambda_x=12.5$ mm. Maximum pressures are 640 and 1000 kPa, respectively, and both pulses describe a total force of 100 N.

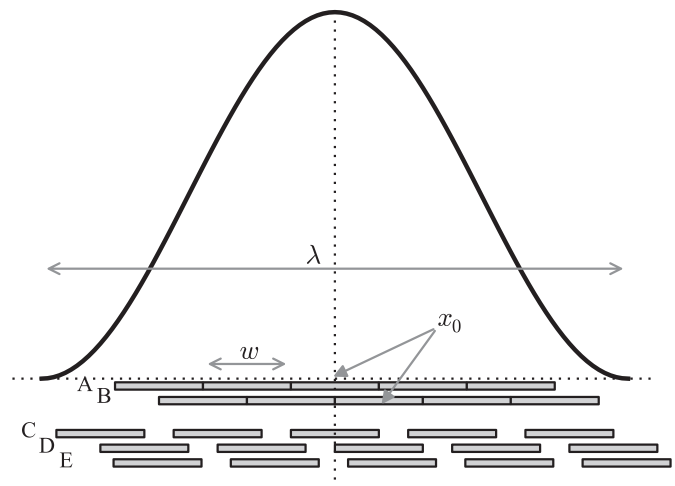

Fig. 2. Model parameters and sensor positioning. A pulse with wavelength λ is to be measured by a square sensor with width w and position x_0 with respect to the pulse maximum. The measured pressure Eq. (3) is the average pressure acting on the sensor surface. (A) Ideal sensor array, centered on the pulse. (B) The same as A, translated by $w/2$. (C) Array of ideal sensors with gaps, centered. (D) The same as C, translated by $w/2$. (E) The same as C, translated by slightly more than $w/2$. Importantly, A and C measurements are equal and best, B and D measurements are equal, and E's measurement is poorest.

Table 1
Glossary.

Category	Symbol	Unit	Description
Model	$f(x,y)$	N mm^{-2}	Distributed load model (1 N mm^{-2}=1000 kPa)
	x,y	mm	Spatial location
	F	N	Total force (see Appendix A)
	λ_x,λ_y	mm	Pulse wavelength (in the x- and y-directions)
	p^*	kPa	Maximum pressure (1 N mm^{-2}=1000 kPa)
Measurement	w	mm	Width of an ideal square sensor
	x_0,y_0	mm	Sensor location relative to the local pressure maximum
	$\hat{p}$	kPa	Measured pressure
Pressure changes	Δp^*	kPa	True local-max difference between two pulses
	$\Delta\hat{p}$	kPa	Measured difference
Accuracy	$\hat{p}/p^*$	%	Local-max measurement accuracy
	$\Delta\hat{p}/\Delta p^*$	%	Pressure change measurement accuracy

2.3. Experiment 1: model validation

Ten subjects (age: 22.0 ± 0.2 yrs, height: 168.6 ± 9.6 cm, mass: 60.8 ± 6.9 kg) were recruited to walk along an 8-m gait runway, at the center of which was a two-meter pressure platform (model: FDM-2, 8.5 mm resolution; Zebris Medical GmbH, Isny, Germany). Subjects were instructed to "walk normally" at a "comfortable pace". Data were collected at 200 Hz. All subjects provided informed consent prior to participation, according to the policies of the Human Research Ethics Committee of Shinshu University.

Only the subjects' left feet were examined. Spatially maximum pressures were computed, and these data were then spatially aligned across trials (Oliveira et al., 2010), yielding one mean pressure distribution per subject. Next, the local maxima at the heel, metatarsals, and hallux were manually digitized, and an algorithmic search followed to find the exact maxima locations.

To compensate for arbitrary postures in the horizontal plane, the foot's principal axes (Fig. 3) were computed as the eigenvectors of the pressure-weighted covariance matrix (Harrison and Hillard, 2000). All data were interpolated with respect to this principal coordinate system using bilinear interpolation (Sonka et al., 2008) at a resolution of 4.25 mm. Local pressure pulses at the heel, metatarsals and hallux were extracted using square windows centered at the local maxima with widths of 30, 20 and 15 mm, respectively.

The model Eq. (1) was then fit to the local pulses in a least-squares sense using a hierarchical implementation of particle swarm optimization (Ratnaweera et al., 2004). To compare the present results to those of Lord (1997), who used only a 1D