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DIRECT MEASUREMENT OF THE CENTRE OF MASS LOCATION IN WALKING PERSONS

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ABSTRACT

The movement of the whole body centre of mass (COM) is the best single descriptor of the movement of the entire human body. To date however, only indirect or derivative based methods have been used to estimate COM movement in human walking. In this study a direct COM location measurement system, comprising an adapted reaction-board technique consisting of a board supported by four load-cells, is described for determining COM location in walking human subjects. Life-sized projections of subjects in various stride positions are used to place subjects into recumbent static walking positions. Multiple static measurements are used to estimate dynamic COM movement. Data of COM oscillation on six male subjects (age 20 - 23 years) walking at 4 km.h^{-1} on a motorised treadmill are presented. These data are the first direct measurements of COM oscillation in walking humans over an entire stride. Data found using other, less direct methods are not dissimilar to the data obtained for COM oscillation in this study (median vertical and anterior-posterior COM oscillation during walking 4.1 cm and 5.4 cm respectively, while median COM height was 99.3 cm above the treadmill surface over one stride duration). In addition, we were unable to detect a significant relationship between the magnitude of vertical or horizontal (forward-back) COM oscillation and stature in our subject group ($R^2<0.1$; $p>0.5$).

Key words: Centre of mass; Walking; Gait.

INTRODUCTION

The centre of mass (COM) of the human body is a physical manifestation of the entire human body and is the point relating to the body that requires the most energy to move from one point to another (when changing the body's inertial properties). Measurements of the location of the COM of a person is often carried out in both the clinical and applied sports domains. The applications of such COM data is essential to a variety of scientific applications such as the study of balance, gait, mechanical work and biomechanical efficiency (Cavagna *et al.,* 1964; Benda *et al.,* 1994; Saini *et al.,* 1998). Indeed, in the South African context, recent attempts have been made to further the understanding of quantification balance (Du Toit & Pienaar, 2001) and energy expenditure (Davies & Mackinnon, 2001), both of which are in part reliant on COM movement.

Various methods of estimating COM location and degree of movement now exist, each technique aligned to specific applications. Conventionally, static measurements of the whole body COM location in living people are made using either a knife-edge method (Borelli, 1679) or a reaction-board (Reynolds & Lovett 1909). Dynamic estimations of the changes in the position of whole body COM are made based on the segmental method of Braune and Fischer (1889), using measurements of the movement of the waist (Belli *et al.,* 1993) or the sacrum (Saini *et al.,* 1998) or derived from ground reaction forces (Shimba, 1984). However, the authors have not found any published data that demonstrate the accuracy of these dynamic measurement methods, where a comparison between known movement of COM and the data obtained using these techniques is made.

Because known positions of COM can be measured in inert objects on a reaction-board, where the actual COM location of the object can be determined, the accuracy of reaction-board measurements is measurable. The reaction-board system is conventionally used to measure COM position in a person in the supine (stationary) position (Hamill & Knutzen, 1995). Reaction-boards have been previously used to measure COM locations of sportsmen in different body positions that corresponded to the body positions seen while performing sports actions (Rasch & Burke, 1967). From this, researchers were able to estimate the different positions of COM in changing postures and could estimate the path of COM during the activity (e.g. diving) (Gowitzke & Milner, 1984). In this manner it was possible to combine data from multiple measurements to generate a description of the dynamic changes in COM location, based on direct COM location measurements.

This study aims to describe the use of multiple static measurements to estimate dynamic COM movement, and to present the first data derived from direct measurements of COM oscillation in walking humans over an entire stride. Secondly, since COM height is sometimes normalised to stature (McDonald & Dapena, 1991; Engsberg *et al*., 1992) the relationship between COM movement and stature was quantified.

METHODS

Board construction and accuracy

A loadcell based reaction-board (2 m x 1.22 m) connected to a four-channel voltage supply, chopper amplifier system (Eagle Electric, PC 68/4, Cape Town, RSA) was constructed. Amplified signals from each load cell were sampled at 100 intervals per second using a 10-reading moving sample average. Data was processed and logged using a computerised data acquisition system (Biopac MP100, Santa Barbara, USA). The position of the COM of objects placed on the board surface was calculated using standard algebraic methods (Hamill & Knutzen, 1995).

The accuracy of the reaction-board system has been quantified in a previous study (McKinon *et al.,* 2004). Errors of COM measurements were shown to be a median of 0.26 cm (0.01-1.09 cm) for the board length and 0.61 cm (0.01-1.54 cm) for the board width. Differences between recorded and known COM displacements (movement of COM between two points) were 0.05 cm (0.004-0.873 cm) and 0.100 cm (0.006-2.015 cm) along board length and width axes respectively. These errors increase to maxima of 1.95 cm and 2.42 cm for COM positions and displacements respectively when error due to image distortion of our system are included.

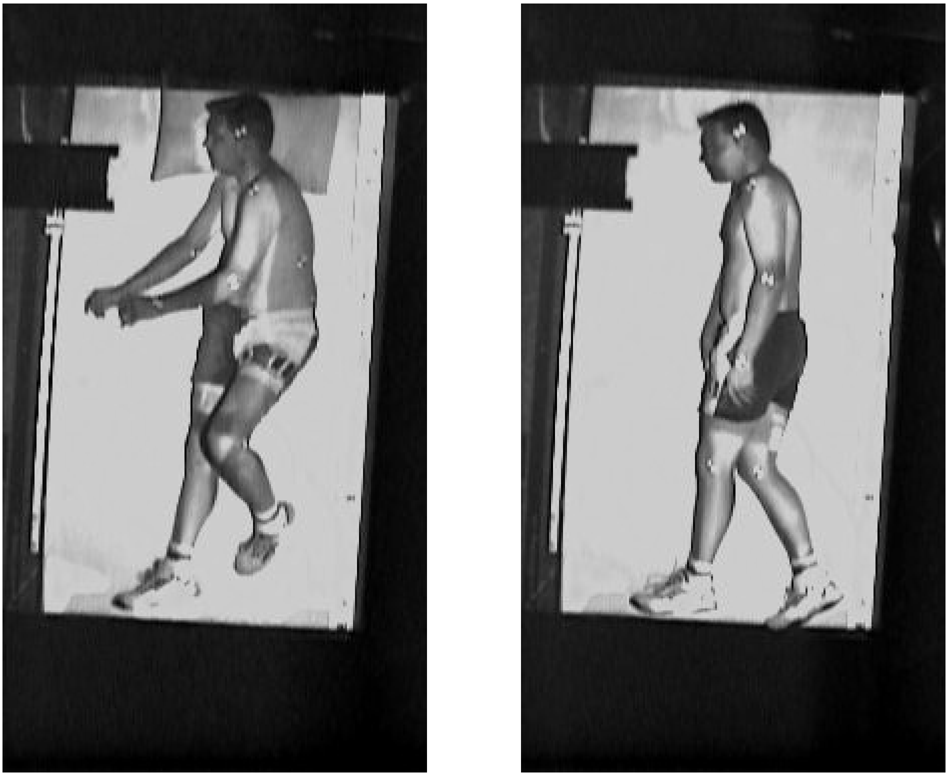
Measurements on walking human subjects

Before participating in this study, all volunteering subjects were fully informed of all experimental procedures and indicated their willingness to participate in the study by signing a consent form, written informed consent was obtained in all cases. Experimental procedures were passed by the Committee for Research on Human Subjects of the University of the Witwatersrand (Clearance number M990241). Centre of mass measurements were made on six healthy male volunteers (age 20 - 23 years, body mass 58 - 97 kg, height 170 - 185 cm), all of whom were accustomed to walking on a treadmill. All subjects walked on a motorised treadmill (Powerjog E10, Birmingham, England) at 4 $km.h^{-1}$ for 2 minutes. The last 10 seconds of each walk was filmed in the left sagittal plane at 50 $frames.s^{-1}$ using a digital camera (Redlake Motion Meter, Morgan Hill, USA), fitted with a 3.5 mm lens and placed 6 m from the treadmill centre, and at a height equivalent to 1 m above the treadmill surface.

Joint centres of all major body segments were marked using markers that were placed on body landmarks of all subjects. Immediately after walking, recorded images were projected onto the reaction-board from above using a digital data projector (Sanyo PLC XU20E, Osaka, Japan). Life sized images of a line that was drawn along the centre of the treadmill belt was aligned to corresponding marks on the reaction-board, to allow for COM position measurements to be related to positions above the treadmill.

Subjects could observe images of themselves filmed from above whilst lying recumbent on their right sides upon the reaction board, with the aid of an online video system and therefore were able to align their markers (and therefore body segments) to those images, recorded while walking on the treadmill. Two independent observers then refined marker placement by ensuring each marker was in alignment with its image. Once both observers and the subject agreed that all markers were aligned, the subject would lie still and COM co-ordinate data were recorded.

Every five minutes subjects were rested to alleviate any discomfort. Subjects were permitted a pillow to support their heads while positioning themselves, which was removed before data collection. After every ten minutes each load cell was tested and adjusted for potential baseline drift.



(a) **(b)**

FIGURE 1. **PHOTOGRAPHS SHOWING THE EXPERIMENTAL PROCEDURE AS SEEN FROM ABOVE. PHOTOGRAPH A) SHOWS A SUBJECT BEGINNING TO ALIGN HIMSELF TO HIS PRE-RECORDED IMAGE. B) SHOWS THE SAME SUBJECT MINUTES LATER, ALIGNED TO HIS OWN IMAGE (HAVING BEEN AIDED BY TWO OBSERVERS)**

Data Analysis

COM data are represented as medians (minimum to maximum in parenthesis). Mean ± standard deviations have been used in the case of parametric variables (time taken to make measurements and the number of frames per subject). Heights of COM are shown as medians of the median height of all points obtained from one subject over one stride. Oscillation data are calculated from the difference between maximum height of COM above the treadmill and minimum heights for every stride.

RESULTS

TABLE 1. **COM OSCILLATION AND HEIGHT OF COM IN SIX WALKING SUBJECTS**.

	Median (min.-max.) (cm)
Vertical oscillation of COM	4.1 (3.5-5.8)
Horizontal oscillation of COM	5.4 (4.2-6.4)
Median Height of COM	99.3 (96.3-107.7)

Measurements on all six subject yielded full walking strides (left foot down to left foot down) in all cases. COM oscillation for all subjects displayed sinusoidal patterns of motion over time with respect to COM height above the treadmill (Figure 2). The time taken to make measurements on each walking stride (Table 1) was a mean of 126 ± 42 minutes (mean 57 ± 5 frames). The magnitude of COM oscillation was poorly correlated with stature along both the vertical (p=0.82) and horizontal (forward – back axis, p=0.58) axes (Figures 3 and 4 respectively). For this reason no attempt to normalise our data to stature was made. The logical relationship between stature and median height of COM over the walking stride was however evident (p=0.038, Figure 5).

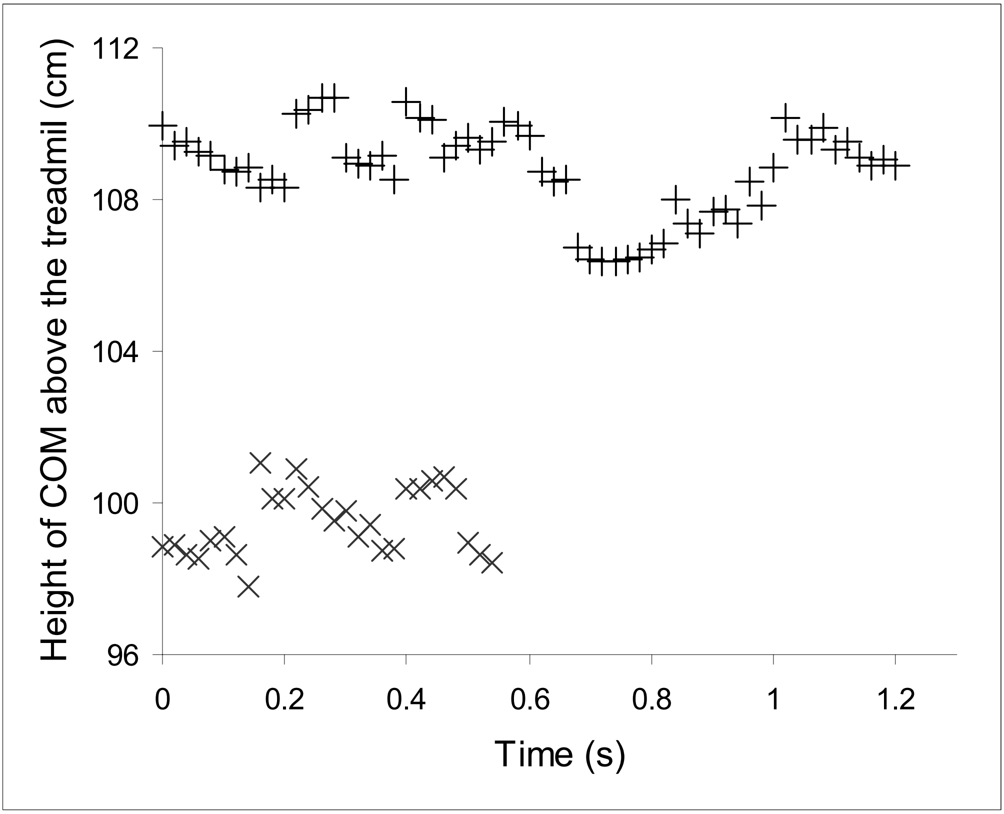


FIGURE 2. **VERTICAL CENTRE OF MASS OSCILLATION OF ONE WALKING STRIDE IN TWO SUBJECTS WITH DIFFERING STATURE USING THE REACTION-BOARD METHOD. THE SUBJECT INDICATED BY (+) WAS OUR TALLEST SUBJECT (STATURE 185 CM). THE SUBJECT INDICATED BY (×) WAS OUR SHORTEST SUBJECT (STATURE 170 CM)**

DISCUSSION

Reaction-board technique and walking COM data

The data represented here are the first recordings of full COM oscillations for walking strides where the accuracy of measurement of COM location data have been verified by comparisons between measurements made with a COM measurement technique (a reaction-board) and known COM positions. The well known sinusoidal pattern of vertical COM oscillation in the sagittal plane (Cavagna *et al.,* 1975; Shimba, 1984; Iida & Yamamuro, 1987; Crowe *et al.,* 1995; Saini *et al.,* 1998) was observed in all cases (Figure 2). Conventionally such estimates of COM movement have been made by two other methods, namely the segmental and force-platform methods, mainly due to their ability to yield descriptive data in reasonable time.

Force platforms are used to measure the relative movement of whole body COM, utilising a double integration of ground reaction forces (Shimba, 1984; Benda *et al.,* 1994). Force platform methods cannot however estimate the position of COM relative to any reference point in space. The latter method is however dependent on accurate estimation of integration constants, accurate measurement of true mass of the subject as well as the gravitational acceleration constant at the site of measurement. This is because any data errors are amplified during the double integration procedure (errors of the second integral are summated throughout the measurement period).

The segmental technique is also reliant on its own subset of assumptions. One of the most important of these is that cadaveric or other artificial data are used to approximate the properties of moving body parts of any subject under scrutiny. Over the last twenty years, a few studies have begun to question the accuracy of segmental derived COM data. In particular Saini *et al.* (1998: 133) discovered “physiologically significant” differences between force platform and segmental COM data. Additionally, Arampatzis *et al.* (2000: 457) stated that “the calculations on the basis of kinematic data cannot be recommended to determine efficiency of movement”. These statements suggest that more investigation into the assumptions inherent to the segmental method is warranted.

In the past, reaction-board methods have been assumed to be entirely accurate (Dempster, 1955; Davis, 1973). We were however able to demonstrate a minor level of error inherent to the reaction-board approach (McKinon *et al.,* 2004). Notwithstanding this, the use of any other accurate direct measurement methods to measure COM location over a walking stride, such as balancing of suspension of a subject, are unrealistic due to the methodological difficulties. The latter difficulties include extended measurement durations and the need for multiple positioning of a subject for a single COM location data point.

Despite the different approaches used between more indirect methods of COM location measurement and our own, COM data generated by such methods are not dissimilar from our reaction-board data. Vertical oscillation of COM of walking subjects, measured on a force platform varies from 1.7 cm to 3.7 cm (Iida & Yamamuro, 1987; Crowe *et al.,* 1995; Saini *et al.,* 1998). Data from segmental estimates show walking COM oscillations of 2.6 to 4.5 cm (Cavagna *et al.,* 1964; Saini *et al.,* 1998). Both of these are comparable to our median COM walking oscillation of 4.1 cm (Table 1). These figure comparisons are encouraging in respect of the segmental and force platform techniques, which are as yet largely of undetermined accuracy.

Relationship between COM and Stature

Previous studies that have investigated the movement of COM during ambulation have chosen to normalise the location of the COM of their subjects to the stature of the individuals under scrutiny (McDonald & Dapena, 1991; Engsberg *et al.,* 1992). Moreover, it is intuitive to believe that a larger individual should have a proportionally exaggerated gait cycle resulting in a proportionally greater COM height and COM oscillation during walking.

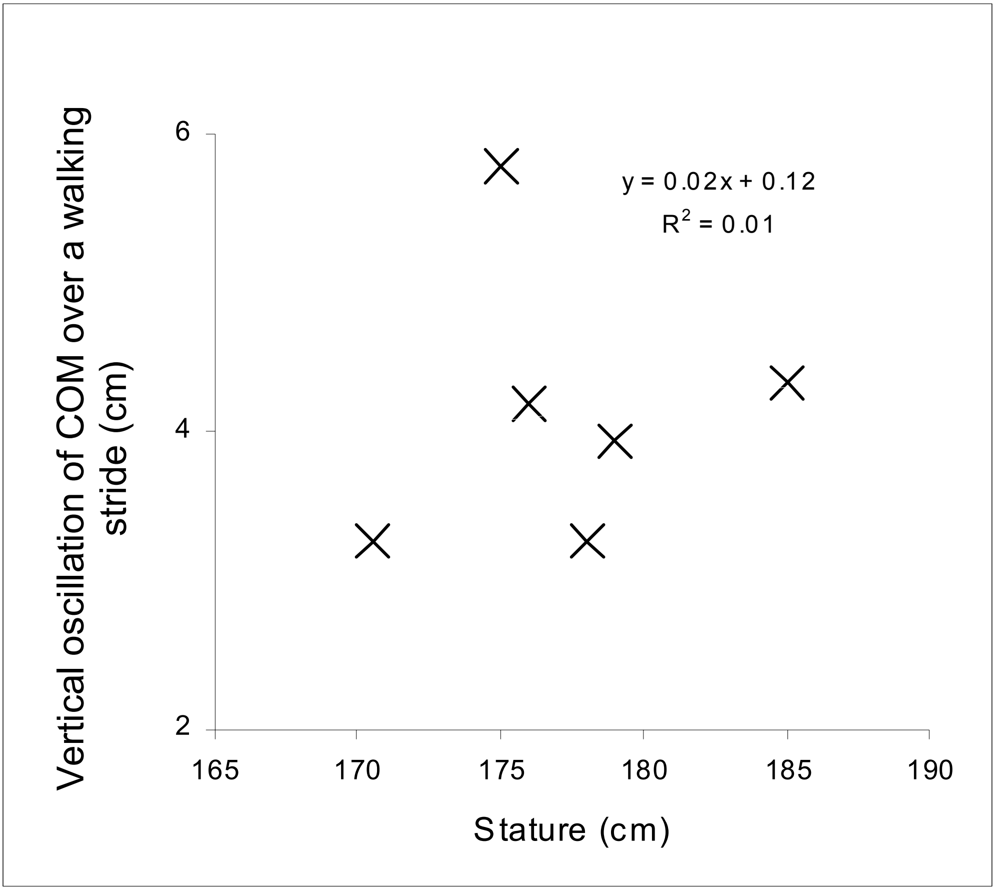


FIGURE 3. **SCATTER PLOT SHOWING THE LACK OF A RELATIONSHIP BETWEEN MEASUREMENTS OF SUBJECT STATURE AND THE VERTICAL COM OSCILLATION OVER ONE WALKING STRIDE IN SIX SUBJECTS**

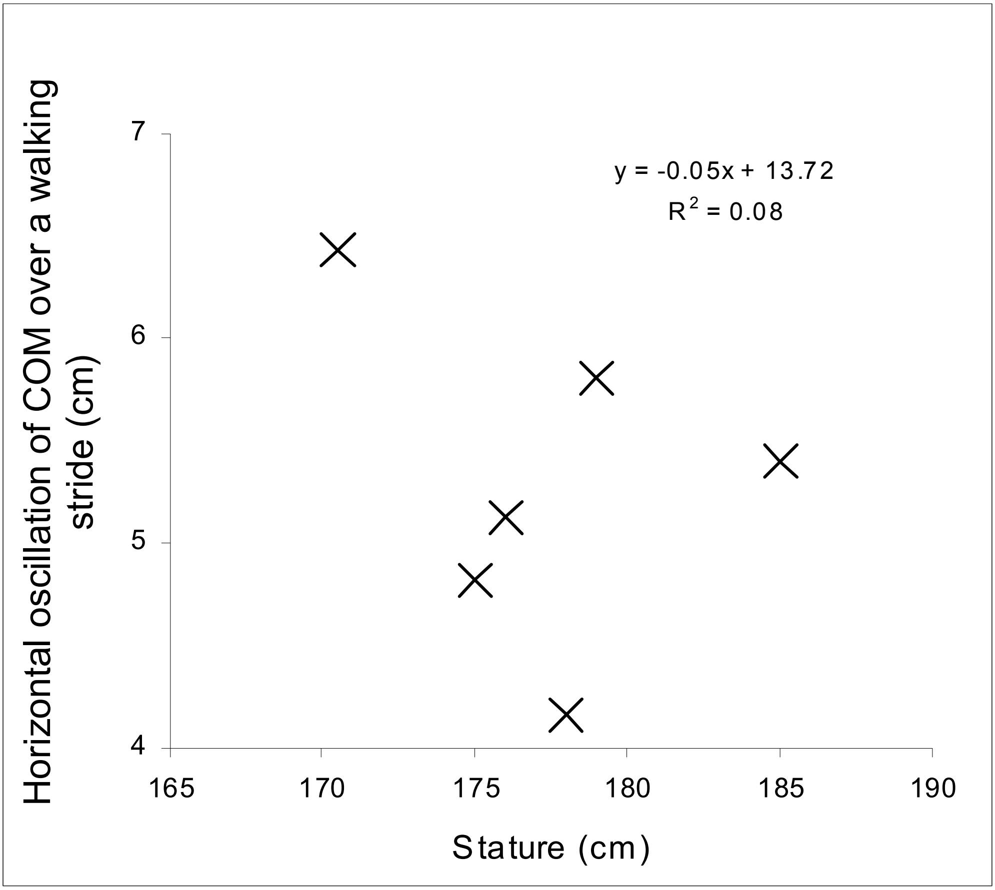


FIGURE 4. **SCATTER PLOT SHOWING THE LACK OF A RELATIONSHIP BETWEEN MEASUREMENTS OF SUBJECT STATURE AND THE HORIZONTAL COM OSCILLATION OVER ONE WALKING STRIDE IN SIX SUBJECTS**

We found no relevant relationship between the degree of COM oscillation and stature (along both vertical and horizontal axes, Figures 3 and 4). This may be due to the small sample size or because the subjects did not undergo preparatory extensive training and accommodation on the treadmill. The explicable relationship between median stride COM height and stature was however clearly observable (Figure 5).

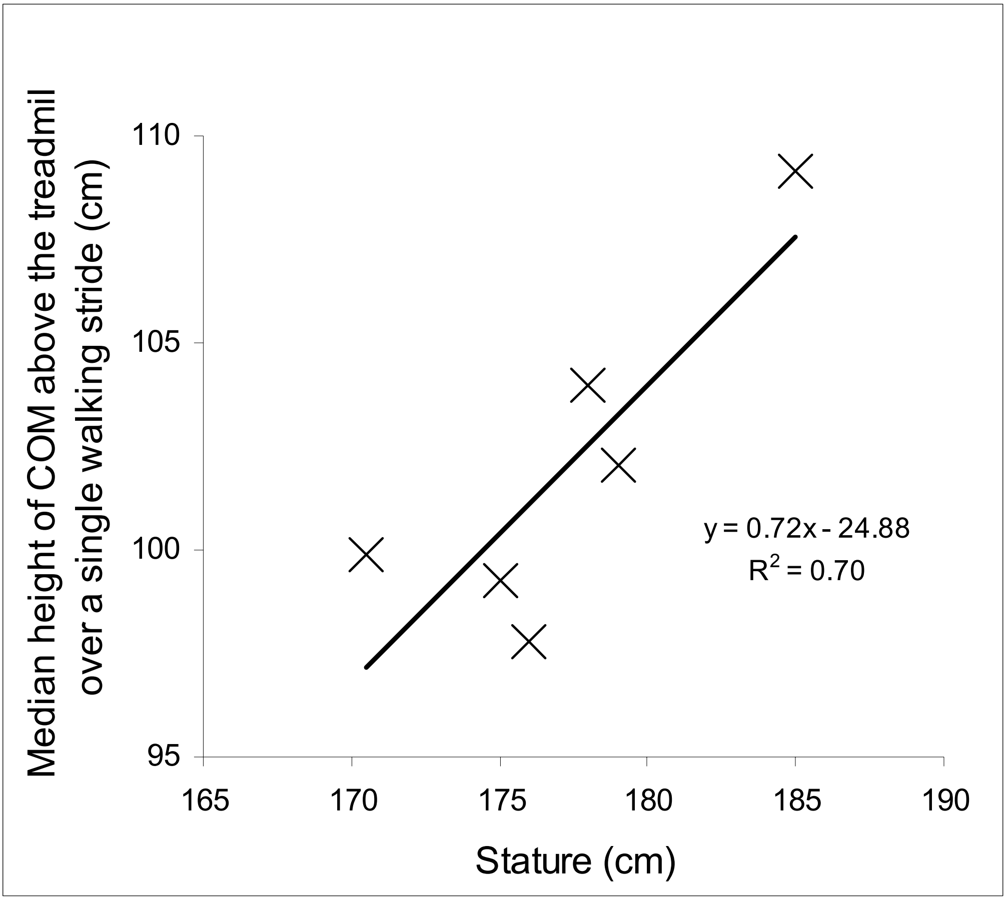


FIGURE 5. **SCATTER PLOT SHOWING THE SIGNIFICANT RELATIONSHIP BETWEEN MEASUREMENTS OF SUBJECT STATURE AND THE MEDIAN COM HEIGHT ABOVE THE TREADMILL OVER ONE WALKING STRIDE IN SIX SUBJECTS**

In conclusion, this study describes the use of multiple static measurements to estimate dynamic COM movement. The data presented are the first direct measurements of COM oscillation in walking humans over an entire stride. The data obtained for COM median vertical COM oscillation during walking are not dissimilar to data found using other, less direct methods. The use of the methods shown here in conjunction with less direct methods may aid in elucidating the possible sources of error of the indirect techniques. Such studies would make it feasible for correction factors to be devised, enabling greater accuracy of the indirect methods enhancing their applicability in both the sports and clinical realms. In addition, we suggest that future research examine the relationship found between the magnitude of vertical or horizontal (forward-back) COM oscillation and stature in larger subject groups than our own.

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