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Short communication

Comparison of body segment models for female high jumpers utilising DXA images

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A R T I C L E I N F O

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A B S T R A C T

In motion analysis of sport competitions, the question is often about the most convenient choice for defining the segment endpoints when no visible landmarks can be used. The purpose of the present study was to determine the location of the body centre of mass (CoM) of female high jumpers by using a high accuracy reaction board and two different segment models: Dempster (1955) and de Leva (1996). Digitising the bony landmarks from the images of dual energy x-ray absorptiometry (DXA) and overhead digital camera were used to compare the digitising accuracy. The location of the CoM determined by a reaction board was 55.88 ± 0.52% of subjects' body height. The segment model of Dempster digitized from DXA images (56.66 ± 0.50%) differed from the reference values of reaction board ($p = 0.004$), whereas the model of de Leva (56.06 ± 0.61%) showed no significant difference. The model of de Leva adjusted for female subjects differed only slightly (0.32%), thus, providing appropriate model for female high jumpers. Since the digitised bony landmarks in the DXA images are obviously very close to the correct locations, the differences in results between the segment models and reaction board is most likely due to inaccuracies in the model itself and/or generalisation of one model to different body structures. When the segment landmarks were estimated without any markers on the body, the results did not differ much from the DXA results.

1. Introduction

In the biomechanical analysis of movement, it is often necessary to know the location of the human body centre of mass (CoM). For motion analysis the whole-body CoM can be obtained if the segmental mass parameters are known. The study of body segment inertial parameters (BSIP) including direct measurement techniques, cadaver methods, mathematical/geometrical models, gamma-scanner method, magnetic resonance imaging (MRI), computed tomography and dual energy x-ray absorptiometry (DXA) has a long history and the techniques used has been widely reported. There are many excellent papers available which cover the older (e.g. Dempster, 1955; Drillis et al. 1964; Clauser et al., 1969; Chandler et al., 1975; Plagenhoef et al., 1983; Reid and Jensen, 1990; Pearsall and Reid, 1994) and newer studies (e.g.; Dumas and Wojtusch, 2018; Durkin, 2008; Erdmann, 2018; Merrill et al., 2019a; Cicchella, 2020; Peyer et al., 2015).

Selection of a proper segment model (for e.g., motion analysis of different type of athletes) needs a good understanding of body segment parameters and body structure of the subjects in question. Already Drillis et al. (1964) stated that the greatest error in obtaining BSIPs is due to variations in body build. Dumas et al. (2007) warned that the scaling equations they obtained should not be used outside the population on which they are based (30 years old males and females in their study). Although the studies on human segmental inertial parameters have focused more on males than females, gender comparisons can also be found (e.g. Nikolova and Toshev, 2007; Challis et al., 2012; Rossi et al., 2013; Winter et al., 2018; Whittaker et al., 2021). Virmavirta and Isolehto (2014) examined the suitability of two famous segment models (Dempster, 1955; de Leva, 1996 from Zatsiorsky et al., 1990) for motion analysis of different groups of physically active people and mentioned that due to inter-individual differences among athlete groups the selection of the segment model for analysis is always a compromise. Comparison between segment models of Dempster and Zatsiorsky can be found in several other BSIP studies as well (e.g. Chen et al., 2011; Hanley and Bissas, 2012; Rossi et al., 2013; Peyer et al., 2015; Adolphe et al., 2017). In a motion analysis a small deviation of the exact location of CoM does not usually affect much the results in the kinematic analyses of the sport events, like Olympic Games (Virmavirta et al., 2005; 2009),

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where the segment parameters and the bony landmarks/joint centres of individuals cannot be measured/marked. However, e.g. in inverse dynamics calculations of joint moments and forces, errors of input data including marker locations, segment inertial properties and joint centre estimates may definitely be of importance (e.g. Rao et al., 2006; Camomilla et al., 2017; Arena et al., 2017; Fritz et al., 2019; Merrill et al., 2019).

Dual energy X-ray absorptiometry (DXA) has been widely used to estimate body segment parameters (e.g. Durkin et al., 2002; Wicke and Dumas, 2008; Kutáč et al., 2019; Merrill et al., 2019a,2019b) and those studies have shown high reliability in measuring body composition parameters. DXA images also enable to locate the bony landmarks/joint centres for the segment models, and therefore, DXA was utilised in the present study. The purpose of the study was to determine the location of the body centre of mass (CoM) of female high jumpers by using a high accuracy reaction board and two different segment parameter models (Dempster, 1955 from Winter 2009; Zatsiorsky et al., 1990 adjusted by de Leva, 1996). The anatomical landmarks of Dempster and de Leva models were determined from both digital camera images and DXA scans.

2. Methods

Nine Finnish national level female high jumpers participated in the study (personal best result 181.9 ± 4.0 cm, age 22.4 ± 2.9, height 176.5 ± 5.6 cm, mass 62.5 ± 2.4 kg, and fat% 17.1 ± 2.6). Subjects were informed about the measurement procedure and provided written consent for the measurements. Images of a dual energy x-ray absorptiometry (DXA, GE Lunar Prodigy Advance, Madison, WI, USA) were used to digitise the exact body landmarks of two different segment models for determination of a location of the body centre of mass (CoM). Results of the segment models (Dempster, 1955 from Winter 2009; Zatsiorsky et al., 1990 adjusted by de Leva 1996) were compared with the true location of subjects' CoMs determined by a high accuracy reaction board (Virmavirta & Isolehto 2014). A comparison was also done between the results when the images were taken by DXA or standard digital camera. This way the digitising accuracy of the landmarks was tested.

The reaction board consisted of knife-edge pivot in the mid region, and a very sensitive force transducer at one end (Fig. 1). Calibration of the reaction board followed the procedure of Virmavirta and Isolehto (2014). A homogenous steel bar (35 kg, 1590 mm) with a known CoM location was moved along the board (Δ 50 mm) covering the range of force values applied to the force transducer in the measurements with subjects (43.73–94.28 N). The difference between the true position of CoM (0.795 m) and the position estimated by the reaction board was less than 1 mm, thus providing a reliable method for determining the CoM reference values (Fig. 2). Subjects lay in supine position on the DXA table and balance board as shown in Fig. 3. An example of calculation of the CoM location (x) on the reaction board proceeds as follows (see Fig. 1):

$$x = \frac{F^{*}L}{mg} = \frac{63.077\text{N}^{*}1.000\text{m}}{611.163\text{N}} = 0.103\text{m}$$

where F is force, L is distance of the force transducer from the pivot point and mg is weight of a subject.

The distance × was then added to subject's heel position from the pivot (0.86 m), and the location of the CoM, 0.963, was 55.83% of subject's body height (1.725 m) in this example. An experienced operator digitized the bony landmarks and joint centers as shown in Fig. 3.

Virmavirta and Isolehto (2014) mentioned that there are often discrepancies in citations made from the original Dempster data where the sum of segments' masses (97.2%) does not match the total body mass. In the present study, the Dempster model was based on the modified data provided by Winter (2009), and mass (% total body mass) and CoM position (% segment length) of the different body segments are presented in Table 1.

In the statistical analysis differences between locations of CoM determined by the reaction board (RB) and two different segment models (de Leva, Dempster) were tested by using a paired two-tailed t-test. Within each segment model, a paired two-tailed t-test was also used to compare the results from digital camera images and DXA scans. A p-value ≤ 0.05 was used as a threshold for significance.

3. Results

The location of the CoM determined by a reaction board was 55.88 ± 0.52% of subjects' stature (Fig. 4). The results for the segment model of Dempster and de Leva were 56.66 ± 0.50 and 56.06 ± 0.61%, respectively digitized from DXA images. The Dempster model differed 1.4% from the reference values of reaction board (p = 0.004). Fig. 5 shows the results when the segment landmarks were estimated (shown in Fig. 3) without any markers on the body. The results obtained from the digital camera images were closer to reaction board results but differed significantly from the results of DXA images for Dempster model (0.5%, p = 0.020).

4. Discussion

Calibration of the reaction board showed that this method provides accurate location of the body's CoM in the longitudinal direction, and it can be used as reference for comparison of the segment models (Fig. 2). The reaction board result of female high jumpers in the present study (55.88 ± 0.52%, Fig. 4) is in good agreement with earlier study of Virmavirta & Isolehto (2014) with the same device for female students of physical activity (55.91 ± 0.88%). The segment model of Dempster differed from the reference values of reaction board (1.4%, p = 0.004). The model of de Leva adjusted for female subjects differed only slightly from the reaction board reference, thus, providing appropriate model for

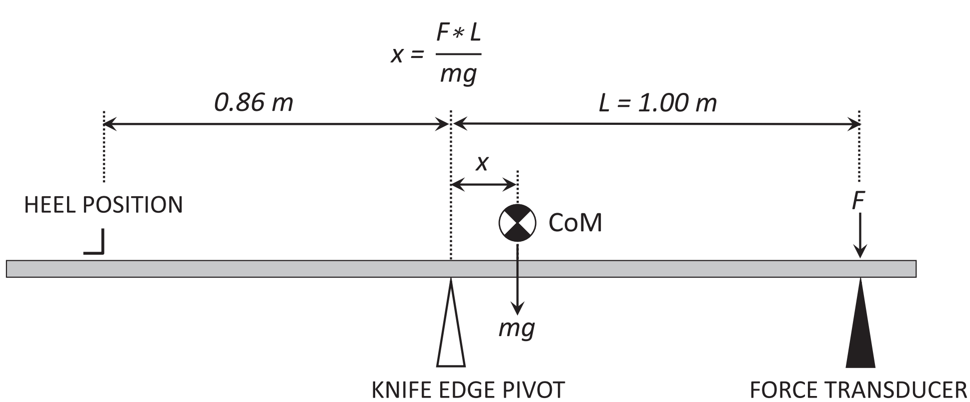

Fig. 1. Calculation of the location of the CoM (x) using moments about the pivot axis.

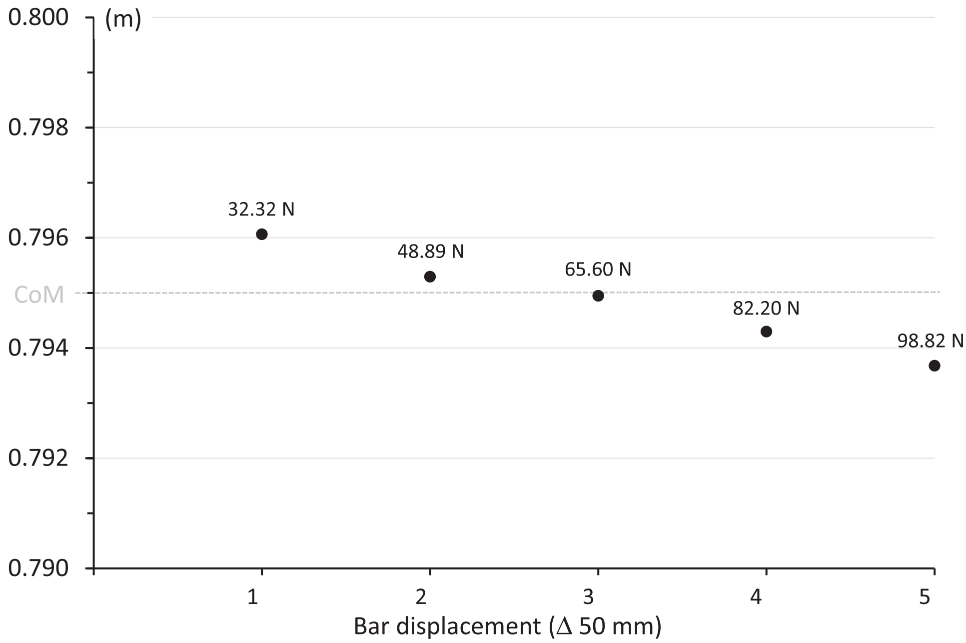

Fig. 2. Calibration of the reaction board. The calibration bar was moved along the board to cover the force transducer readings measured with subjects. The true CoM was at 0.795 m.

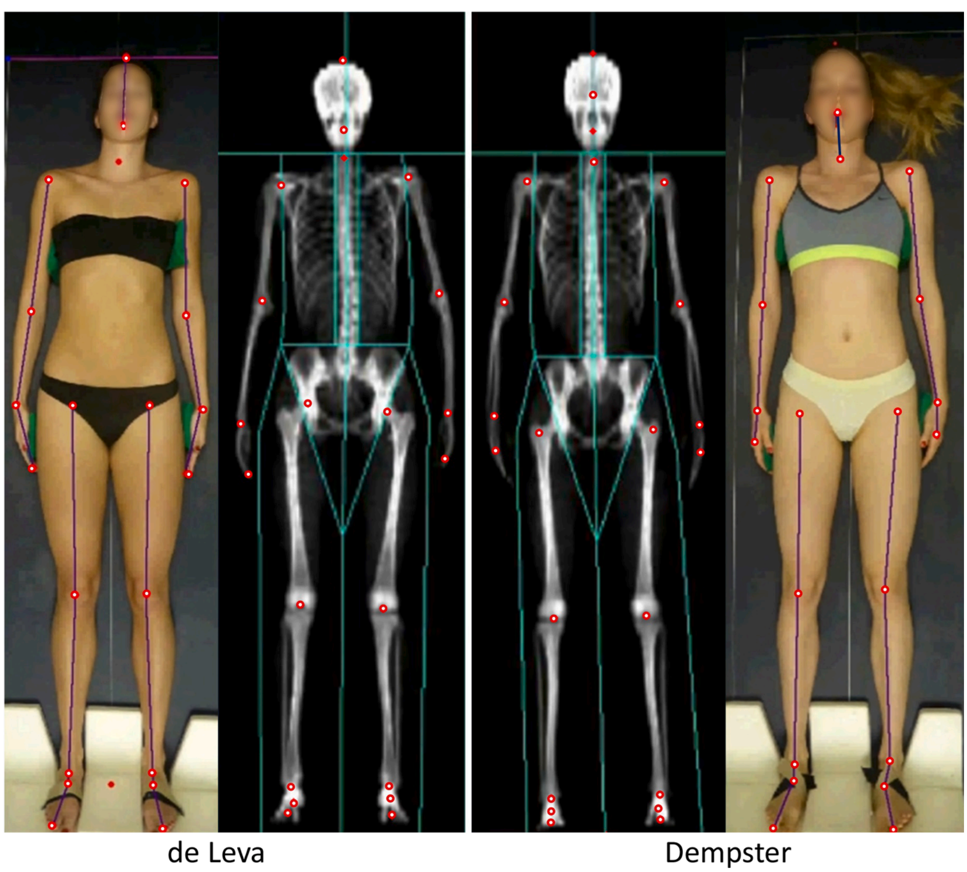

Fig. 3. Schematic examples of the digitised 2D segment model landmarks for the DXA and digital camera images (left: de Leva, right: Dempster).

female high jumpers. The differences between the segment models and between the imaging methods found in the present study, although significant, were very small, and their practical relevance depends on the intended use of CoM locations. In most cases the impact of differences is minor, but in torque calculations where, e.g., the lever arms are needed, the above-mentioned difference of 1.4%, meaning 13.8 mm in subjects' average stature, may be important.

Different results for two segment models can be explained by the

Table 1
Body segment parameters. Segment masses are relative to total body mass and segment CoM positions are referenced to proximal endpoints relative to segment lengths.

			de Leva et al. 1996 (adjusted from Zatsiorsky et al. 1990)				Dumpster 1955 (from Winter 2009)	
Segment	Endpoints		Mass (%)		CoM (%)		Mass (%)	CoM (%)
			Male	Female	Male	Female		
Head	VERT	MIDG	6.94	6.68	59.76	58.94	8.10	43.3
Trunk	MIDS	MIDH	43.46	42.57	43.10	37.82	49.70	49.5
Upper arm	SJC	EJC	2.71	2.55	57.72	57.54	2.80	43.6
Forearm	EJC	WJC	1.62	1.38	45.74	45.59	1.60	43.0
Hand	WJC	MET3	0.61	0.56	79.00	74.74	0.60	50.6
Thigh	HJC	KJC	14.16	14.78	40.95	36.12	10.00	43.3
Shank	KJC	LMAL	4.33	4.81	44.59	44.16	4.65	43.3
Foot	HEEL	TTIP	1.37	1.29	44.15	40.14	1.45	42.9
			100.00%	100.00%			100.00%	

VERT (vertex), MIDG, MIDS, MIDH (mid-gonion, mid-shoulder, mid-hip – the points midway between the gonions and joint centres), SJC, EJC, WJC, HJC, KJC, (the joint centres of shoulder, elbow, wrist, hip, knee), MET3 (3rd metacarpale), LMAL (lateral malleolus), TTIP (the tip of the longest toe).

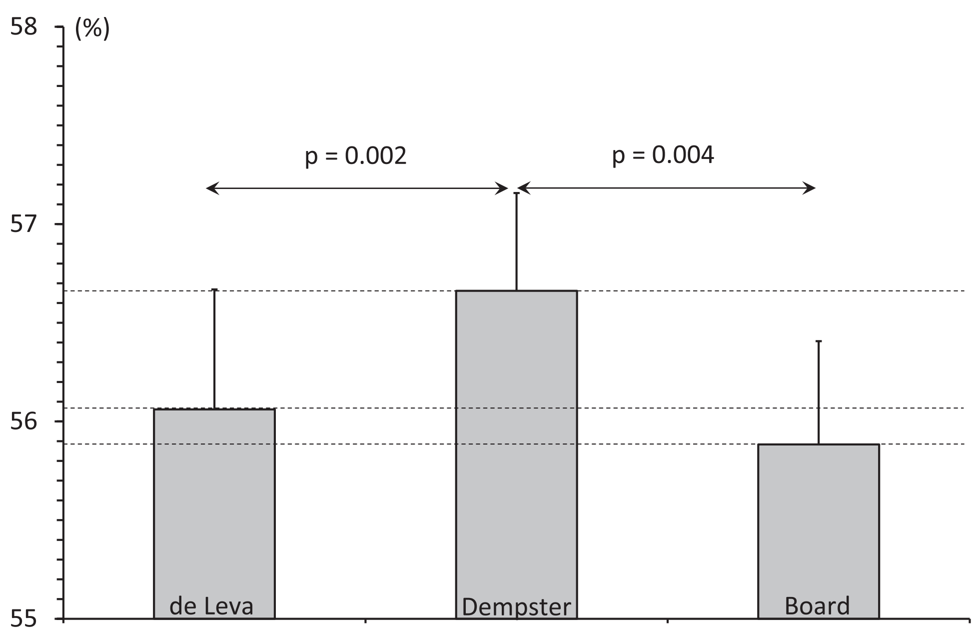

Fig. 4. Location of the body's centre of mass (CoM, percentage of the body height) determined by the reaction board (RB) and two different segment models used in the digitised DXA images.

different mass distribution of trunk (49.70 and 42.57% of the total body mass for the model of Dempster and de Leva, respectively) and thigh (10.00% and 14.78%) segments in the models. Okada et al. (2013) using 3D body scanner, found mass of the thigh segment of 13–15% for elite female athletes (n = 123) of 18 various competitive events, which supports de Leva's estimation. Arena et al. (2017) found that, in the thigh, de Leva's segment endpoints tended to locate the COM more proximally (17.2%) than DXA estimates in collegiate female soccer players. However, the authors concluded from their drop jump experiments, "Although BSIP estimation may vary between estimation methods, the resulting impact on knee joint moment and power calculations, even during dynamic tasks with large accelerations, is negligible". Fritz et al. (2019) investigated the effect of the BSIP input on the accuracy of the inverse dynamics modelling during an athletic movement with high segment acceleration. Their group specific model of optimized set of BSIPs for ski jumpers showed that even a simple optimisation of only the trunk and the thigh segments increased the accuracy of take-off forces as compared to the best performing published model of Zatsiorsky and Seluyanov (1985). The authors stated that the results of inverse dynamics modelling are very sensitive to the BSP estimation and they emphasized the importance of selecting adequate BSPs when analysing specific groups in highly dynamic movements.

Slightly too high location of CoM for de Leva's model in the present study may be caused by the trunk segment CoM position in the model (37.82% as referenced to cranial endpoint of the segment). According to Wicke et al. (2009) using DXA as standard for 25 female college-aged participants, the average trunk centre of mass location appears to be around half the trunk's length. Erdmann and Kowalczyk (2015,2020) have discussed the "trunk problem" in details, and their main concern has been treatment of the trunk as a one segment although it constitutes about half of the body mass. By dividing the trunk into more subportions and using Erdmann's method (Erdmann, 1997) the authors concluded that an accurate location of the centre of mass can be obtained in situations e.g., for raised shoulders, for an arched body (high jumper as an example) and for people of different gender. According to Erdmann and Kowalczyk (2015,2020) raising of shoulders will involve about 20% of the whole trunk mass and therefore, arched trunk and shifting of a shoulder give the reason to divide the trunk into more parts. They recommended analysing the trunk between hip joints up to the border of the trunk and neck, despite position of the arm joints.

In motion analysis of sport competitions, the question is often about the most convenient choice for defining the segment endpoints when no visible landmarks can be used, and this is most likely why the trunk is presented only as one segment. The direct comparison between the

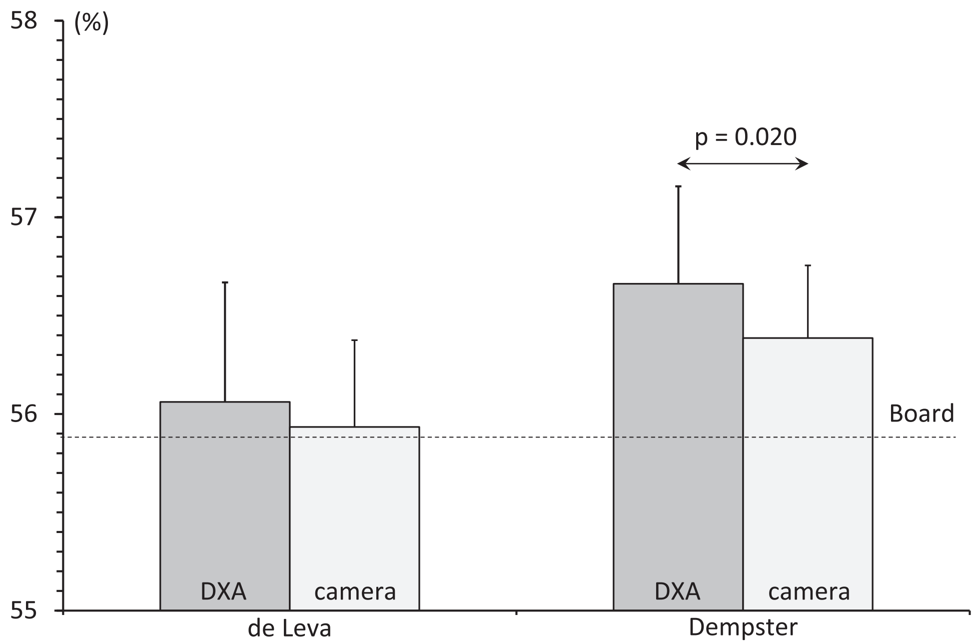

Fig. 5. Comparison of the location of the body's center of mass (CoM, percentage of the body height) between the digitised images (DEXA/camera) for the segment models.

models is often difficult due to the different segment endpoints used. DXA scans, which are used primarily to evaluate bone mineral density and total body composition and fat content, also provide a good tool to evaluate the different segment models based on bony landmarks. Since the digitised bony landmarks in the DXA images of the present study are obviously very close to the correct locations, the differences in results between the segment models and reaction board is most likely due to inaccuracies in the model itself and/or generalisation of one model to different body structures of the subjects.

The results of estimated segment landmarks without any markers on the body did not differ much from the reaction board results. The most difficult point to digitise is the landmark in the hip area (Fig. 3) as this point separates two biggest masses (trunk and thigh segments), but however, the results of the present study show that also this landmark can be estimated accurately from the camera image.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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