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Use of adult anthropometric tables to estimate children body segment inertial parameters

Sabrina Otmani^{a,b}, Guilhem Michon^b and Bruno Watier^{a,c}

^aLAAS-CNRS, Université de Toulouse, CNRS UPS, Toulouse, France; ^bUniversité de Toulouse, CNRS, ICA, ISAE-SUPAERO, Toulouse, France;

^cDepartment of Information Technology and Human Factors of the AIST, CNRS-AIST JRL (Joint Robotics Laboratory) IRL, Tsukuba, Ibaraki, Japan

ABSTRACT

There is a lack of knowledge in the literature concerning Body Segment Inertial Parameters (BSIP) for children aged 4 to 15 years. Nevertheless, these data are fundamental for studying the dynamics of the healthy and pathological musculoskeletal system. One common method for obtaining BSIP is to use regression equations derived from anthropometric tables. However, the majority of these equations are based on adult data. In this study, we compared certain BSIP (segment mass, center of mass position, and transverse moment of inertia) derived from adult anthropometric tables with the corresponding BSIP extracted from a pediatric anthropometric table. The goal of this study was to determine the accuracy of using adult anthropometric tables to calculate pediatric BSIP. For this comparison, we assessed the proximity of several adult anthropometric tables to a pediatric anthropometric table by Jensen (1986) for each BSIP. Our results revealed differences between the BSIP obtained using adult tables and the BSIP obtained with the pediatric table used as a reference. When considering all the tables, the mean relative difference was 12% for segment mass, 12% for center of mass position, and 25% for transverse moment of inertia. Notably, the greatest relative differences were observed for the head, hand, and foot segments. Additionally, the relative difference in female data was higher compared to males. This result could be attributed to the predominant use of male subjects in the adult tables considered in this study. Finally, the adult anthropometric tables by Dumas and Wojtsuch (2018) and De Leva (1996) provided results that were closer in comparison to Jensen (1986).

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Segment mass; center of mass; moment of inertia; regression equations

1. Introduction

Body Segment Inertial Parameters (BSIP) such as masses of the segments, positions of centers of masses (CoM), and moments of inertia or segment lengths are essential parameters to compute accurate kinetics parameters and provide inverse dynamics process as in Rao et al. (2006) and Muller et al. (2017) because they can have a huge impact on the output of these processes. BSIPs play a crucial role in modeling processes as they can be a variable that can be studied for balance analysis during human motion or dynamic motion simulations. Additionally, they enhance our understanding of motor control of the computed model based on the BSIP, for example in the case of assistive technologies such as exoskeletons (Amiri et al. 2019). There are several ways to determine BSIP. On a first approach, the previous authors used subject specific methodology like dynamic calibration (Bonnet et al. 2016), mathematical models (Hatze 1980) or imaging technology (Ganley and Powers 2004; Pillet et al. 2010).

However, the most common and accessible method to obtain BSIP of healthy subjects consists in leveraging anthropometric tables obtained from analysis of medical imaging, measurements on living subjects or human cadavers based on the total mass, subject's height and segment lengths (Dempster 1955; Clauser et al. 1969).

Among authors, dissimilarities were observed in populations studied such as the number of subjects, the gender, the age, the segment model or the segment reference frame definition (Dempster 1955; Clauser et al. 1969; Chandler et al. 1975; de Leva 1996; Dumas and Wojtsuch 2018) which explain large differences between tables. Moreover, limited information is available regarding BSIP for children or females as most of the anthropometric tables were based on male adults over 18 years. Also, when analysing paediatric tables, none of them provide full BSIP information: segment lengths, CoM locations along the three axes and complete inertia matrix with accurate definitions of the segment reference frame.

CONTACT Sabrina Otmani  sabrinaotmani@gmail.com  LAAS-CNRS Université de Toulouse, CNRS UPS 7, avenue du Colonel Roche BP 54200 31031 Toulouse cedex 4, France

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Thus, the main objective of this paper consists in determining if adult anthropometric tables can be used to replicate and therefore complete the missing children BSIP.

2. Related work and literature

To address such objective, the most complete anthropometric tables for children, Jensen (1986) adjusted from Jensen (1978), was compared with the most used and complete anthropometric tables based on adult data. Indeed, Jensen (1986) is the only paper which provides regression equations based on paediatric data. The other papers which focused their work on paediatric data provides a huge amount of raw data (Corsi et al. 2017; Asif et al. 2018) for a precise population but not regression equations. Jensen (1986) is based on male paediatric data and does not present female data. However, this study presents heterogeneous shape and bodies of male children and proposes an answer to the lack of information about “children’s kinetic” so both genders can be studied. However, as long as Jensen (1986) does not provide explicitly female data, we first need a comparison between paediatric male and female anthropometric data. In that respect, as presented in Table 2, the differences between male and female heights and weights are minor in the beginning (4–14 years old) and start to increase with the puberty. As it may not be common or appropriate to use male data to obtain female ones, we check the accuracy of this possibility in this manuscript. We therefore determined BSIP for male and female children using the same regressions equations of Jensen (1986) and compare them to male and female adults. The use of Jensen (1986) as the reference for paediatric data can be justified by the 3 previous points.

Adult anthropometric tables considered (Table 1 for the comparison are:

Table 1. Adult anthropometric tables considered for each BSIP : segment mass, segment transverse moment of inertia and segment center of mass.

Anthropometric tables	BSIPs		
	Segment mass	Segment transverse moment of inertia	Segment center of mass
Dumas and Wojtsuch (2018)	x	x	x
de Leva (1996)	x	x	x
Dempster (1955)	x	x	x
Clouser et al. (1969)	x		x
Chandler et al. (1975)	x	x	x

- Dumas and Wojtsuch (2018) adjusted from the data of McConville (1981) and Young et al. (1983)
- de Leva (1996) adjusted from the data of Zatsiorsky et al. (1990)
- Clouser et al. (1969)
- Chandler et al. (1975)
- Dempster (1955)

Three available BSIP components (segment masses, CoM locations and inertia about the transverse axis) extracted in the reference table for children of Jensen (1986) were compared with the equivalent parameters of adults anthropometric tables. Jensen (1986), Dumas and Wojtsuch (2018) and de Leva (1996) studies considered a 16-segment model, while studies Clouser et al. (1969) and Chandler et al. (1975) considered a 14-segment model and Dempster (1955) considered a 17-segment model to compute the BSIP. To standardise, some segments were therefore gathered to realize the comparison: thorax, abdomen and pelvis were gathered to allow the study of the trunk considered as a rigid body. The trunk mass is computed as the sum of the three previous segments, the position of the center of mass as the barycenter of the system Thorax-Abdomen-Pelvis and the transverse moment of inertia was computed using the parallel axis theorem also named “Huygens Theorem”. Thus, the three BSIP were computed here for a model involving 14 segments (Figure 1). The definition of the body segment length, including the proximal and distal points of each rigid body segment in this paper are similar to the ones defined in Dumas and Wojtsuch (2018) as this paper provides comparison with de Leva (1996) and Dempster (1955) with the accurate modifications. Modifications and computations were done with Jensen (1986), Chandler et al. (1975) and Clouser et al. (1969) to allow the comparison.

The study of Jensen (1978) was based on 12 living boys subjects between 4 and 15 years old representing heterogeneous body types realised over 3 years for a total of 36 observations. BSIP were estimated using the elliptical zone technique and a photogrammetric method.

Regarding the adults table, Zatsiorsky et al. (1990) measured the BSIPs by frontal gamma-ray scanner on 100 males (mean age: 23.8 yrs; mean mass: 73 kg; mean stature: 1.74 m) and 15 females (mean age: 19 yrs; mean mass: 61.9 kg; mean stature: 1.73 m). Dempster (1955) measured the BSIPs of 8 male cadavers (mean age: 68.5 yrs; mean mass: 61.1 kg; mean stature: 1.69 m). McConville (1981) and Young et al. (1983) indirectly measured the BSIPs by photogrammetry on 31 males (mean age: 27.5 yrs; mean mass: 77.3 kg; mean stature: 1.77 m) and 46 females (mean age: 31.2 years old; mean mass: 63.9 kg; mean stature: 1.61 m). For Clouser et al. (1969), p. 13 male cadavers were dissected into 14

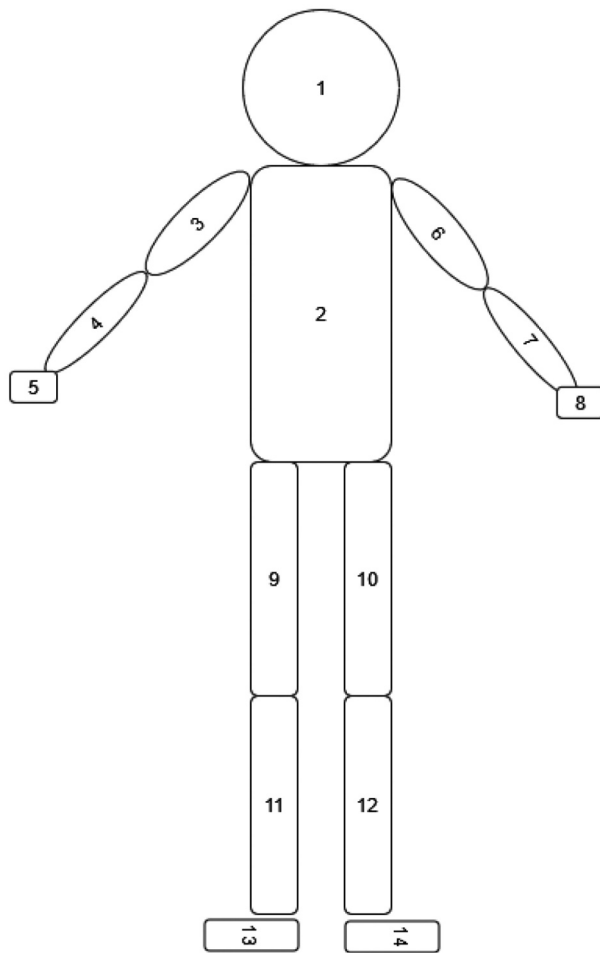


Figure 1. Simplified representation of the 14-segments model. Left and right limbs are merged in the study.

segments (mean age: 49.3 yrs; mean mass: 66.52 kg; mean stature: 1.72 m). For Chandler et al. (1975), p. 6 male cadavers were studied (mean age: 54.3 yrs; mean mass: 65.173 kg; mean stature: 1.72 m). Methods and techniques used for this study are similar to the ones used in Clauser et al. (1969).

3. Method

In this part, we define each BSIP and the computation of mean relative difference between the adult anthropometric tables and the paediatric table reference Jensen (1986).

In Jensen (1986), the three BSIP parameters were computed by using regression equations where the age is a variable parameter. Thus, in this study, virtual children aged from 4 to 15 years were created based on the growth curves of caucasian children (dataset of AFPA-CRESS/Inserm (2018)). The characteristics of the virtual children are presented in Table 2. Those masses and heights represent the mean body mass and height of caucasian children used in this study for each age.

In the adults anthropometric tables, the BSIP parameters were constant and independent with age. Thus, only body mass and height were used to compute BSIP with the adults anthropometric tables while age is a necessary input in the reference table of Jensen (1986). Body segment parameters are expressed as a proportion of subject height, mass or segment length.

The Table 1 summarizes the tables used to realize this comparison for each BSIP. Clauser et al. (1969) does not provide information about the segments transverse moment of inertia so this parameter was not considered for the comparison.

3.1. Segment mass

For the adult anthropometric tables, the segment mass is expressed here as, for each segment, a proportion of the total body mass. For Jensen (1986), the mass of each segment was calculated using the given equations of regression dependent on age. As a reminder, the trunk was analysed as one rigid segment.

3.2. Segment center of mass

The center of mass is defined here along the superior-inferior axis as a percentage of the segment length regarding the proximal segment endpoint. Chandler et al. (1975) provide informations about the center of mass of each segment for each subject but no regression equations. The relative mean position of the center of mass in this adult anthropometric tables is defined as a percentage of the segment length regarding the proximal endpoint for each segment among all the subjects.

Table 2. Mean body mass and height from 4 to 15 years old for both genders calculated from dataset of AFPA- CRESS/Inserm (2018).

Age (Years)	Masses and heights			
	Males Body Mass (Kg)	Female Body Mass (Kg)	Males Height (cm)	Females Height (cm)
4	16.5	16.0	104	103
5	18.7	18.3	111	110
6	20.8	20.7	117	116
7	23.5	23.0	123	122
8	26.0	26.0	129	128
9	29.2	29.3	135	134
10	32.7	32.5	140	140
11	37.0	36.0	145	146
12	40.0	41.0	151	152
13	45.3	46.0	157	158
14	51.0	50.0	164	161
15	56.0	52.7	169	162

3.3. Segment transverse moment of inertia

Clauser et al. (1969) does not report data for the moment of inertia and was not considered for this BSIP. The moment of inertia is a radius of gyration expressed as a percentage of the segment length, determined at the segment center of mass.

3.4. Mean relative difference computation

For each BSIP, the relative difference for each segments between adults and paediatric tables was computed as:

$$\text{BSIP_mean_relative_difference}_x = \left(\sum_{n=1}^N \frac{|BSIP_{Jensen_n} - BSIP_{X_n}|}{BSIP_{Jensen_n}} \right) / N$$

with:

BSIP= the BSIP considered in the equation

N= the number of segments (N = 14)

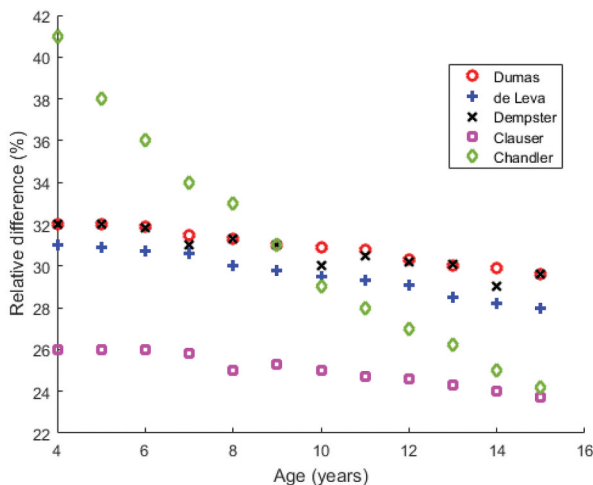
X= the adult anthropometric table considered.

All values have been rounded to tenths in the manuscript.

4. Results

4.1. Segment mass

Our results show that the relative difference between the adult anthropometric tables of Dumas and Wojtsuch (2018) and de Leva (1996) regarding the paediatric table of Jensen (1986) decreases from 4 to 15 years old in most segments. On the opposite, Dempster (1955) and Clauser et al. (1969) present a higher relative difference at 15 years old compared to 4 years old. For distal limbs such as head, feet and



hands, the adult anthropometric tables have a highest mean relative difference with Jensen (1986) than for more proximal limbs (thigh, shank) (Figure 2). And this point is seen for both genders when the female gender can be studied.

The mean relative difference of the segment mass among all segments are $22.2 \pm 4.2\%$ for Dumas and Wojtsuch (2018), $23.0 \pm 3.5\%$ for de Leva (1996), $20.4 \pm 1.6\%$ for Dempster (1955), $20.9 \pm 1.0\%$ for Clauser et al. (1969) and $31.4 \pm 11.7\%$ for Chandler et al. (1975).

Dumas and Wojtsuch (2018) is one of the closest anthropometric tables compared to Jensen (1986) regarding the mean relative difference among all segments and the closest for the trunk, shank, thigh and lower arm (Table 3).

A maximal difference of $28.0 \pm 2.3\%$ over ages is observed for females while $21.0 \pm 3.1\%$ is noted for males between Jensen (1986) and Dumas and Wojtsuch (2018). Additional content at the end of this paper for this BSIP was added for each age, each segment and each adult anthropometric table (Table 11).

4.2. Segment center of mass

The highest relative difference is for the hand and the forearm while it is lower for the trunk, the shank and the thigh (Figure 3).

Clauser et al. (1969) and de Leva (1996) are the closest anthropometric tables with a mean relative difference among all segments respectively of $9.2 \pm 0.3\%$ and $11.2 \pm 0.4\%$. For Dumas and Wojtsuch (2018), Chandler et al. (1975) and Dempster (1955), the mean relative

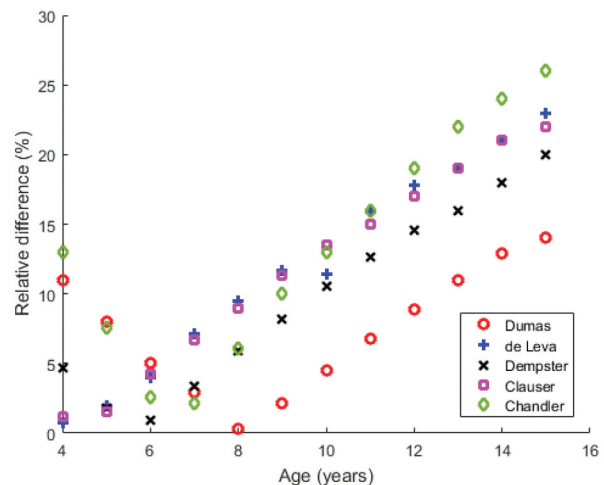
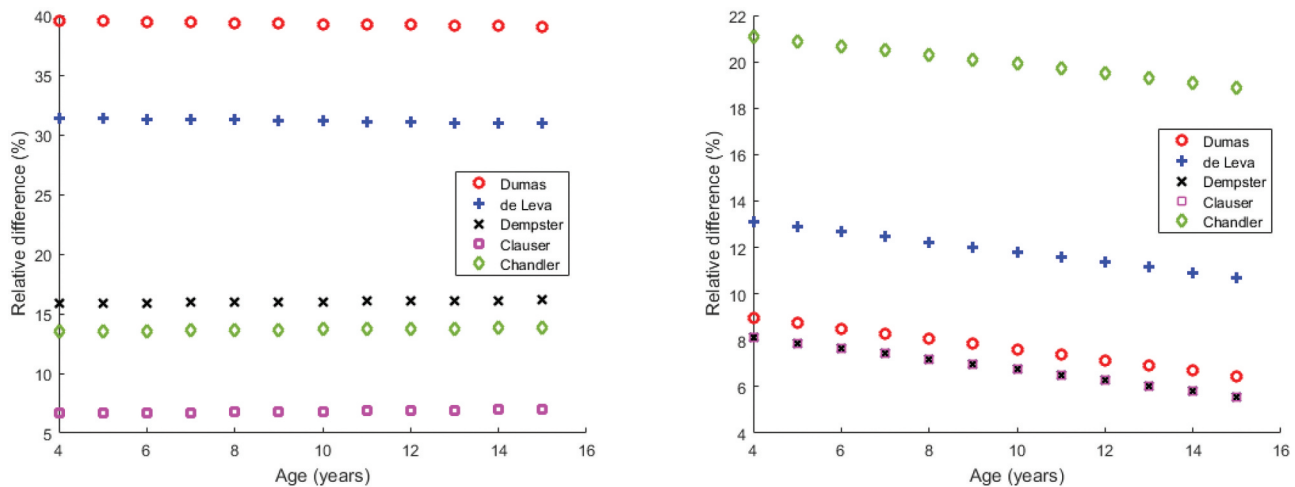


Figure 2. Hand (left) and shank (right) mass relative difference from 4 to 15 years old for the males.

Table 3. Mean relative difference between the adult anthropometric tables and Jensen (1986) from 4 to 15 years old of the segment mass, for all segments.

Anthropometric tables	Age (years)											
	4	5	6	7	8	9	10	11	12	13	14	15
Dumas and Wojtsuch (2018) (%)	28.9	27.5	26.1	24.8	23.4	22.6	21.7	20.8	19.7	18.4	17.1	15.3
de Leva (1996) (%)	28.9	27.1	25.6	24.8	24.0	23.3	22.6	21.9	20.9	19.8	17.5	17.4
Dempster (1955) (%)	20.5	19.1	18.7	18.8	18.9	19.4	20.2	20.8	21.1	21.2	21.2	24.5
Clauser et al. (1969) (%)	22.7	21.1	21.3	21.1	20.7	20.0	20.1	20.0	20.1	20.3	22.7	21.9
Chandler et al. (1975)(%)	57.2	48.1	41.1	34.9	30.9	27.3	25.6	24.1	22.9	21.6	21.5	21.5

**Figure 3.** Hand (left) and thigh (right) center of mass (percentage of the segment length) from 4 to 15 years old for the males.

difference is respectively of $13.9 \pm 0.5\%$, $17 \pm 1.7\%$ and $11.3 \pm 0.2\%$ (Table 4).

Dumas and Wojtsuch (2018) is the closest table for the trunk, the thigh, the shank and Clauser et al. (1969) is the closest for the foot, hand and head (Table 5).

For the females data, the mean relative difference were computed for de Leva (1996) ($10.7 \pm 1.2\%$) and Dumas and Wojtsuch (2018) study ($15.3 \pm 0.9\%$) with the Jensen (1986) study. Additional content at the end of this paper for this BSIP was added for each age, each segment, and each adult anthropometric table (Table 10).

4.3. Segment transverse moment of inertia

The highest relative difference is for the foot and the hand for all of the adults' anthropometric tables (Table 6). Regarding the mean relative difference, among all the segments, the closest adult table to the reference table of Jensen (1986) is Chandler et al. (1975) with a mean relative difference for males data among all segments around $21.0 \pm 0.1\%$. Dumas and Wojtsuch (2018), de Leva (1996) and Dempster (1955) have respectively a mean relative difference of $33 \pm 0.3\%$, $28.6 \pm 0.2\%$ and $21.4 \pm 0.8\%$ (Table 7

For the females, the mean relative difference is $27.9 \pm 0.2\%$ for de Leva (1996) and $36.6 \pm 0.5\%$ for Dumas and Wojtsuch (2018).

Additional content at the end of this paper for this BSIP was added for each age, each segment and each adult anthropometric table (Table 11).

4.4. Among all BSIPs

Table 8 quantifies how far an adult anthropometric table can be to a children anthropometric table considering males data. We can see that the mean relative difference among all segments and considering all the adult anthropometric tables is around $19.5 \pm 3.2\%$. Dumas and Wojtsuch (2018) presents the highest relative difference with important standard deviation. The mean relative difference of Clauser et al. (1969) is not representative because some BSIPs are missing (*).

5. Discussion

There is not an adult anthropometric table which is close to the reference children table of Jensen (1986) for all the parameters Table 9.

Table 4. Mean relative difference between the adults anthropometric tables and Jensen (1986) from 4 to 15 years old of the segment center of mass, for all segments.

Anthropometric tables	Age (years)											
	4	5	6	7	8	9	10	11	12	13	14	15
Dumas and Wojtsuch (2018) (%)	14.9	14.7	14.5	14.4	14.2	14.1	13.9	13.7	13.5	13.4	13.3	13.2
de Leva (1996) (%)	10.7	10.7	10.8	10.9	10.9	11.1	11.2	11.4	11.5	11.7	11.8	11.9
Dempster (1955) (%)	11.2	11.1	11.1	11.0	11.1	11.2	11.3	11.4	11.4	11.5	11.6	11.7
Clauser et al. (1969) (%)	9.3	9.1	8.9	8.8	8.9	9	9.1	9.2	9.3	9.4	9.6	9.8
Chandler et al. (1975) (%)	16.8	16.7	22.1	16.5	16.4	16.3	16.2	16.1	15.9	15.9	18.1	18.1

Table 5. Mean relative difference for the center of mass of each segment for males between from 4 to 15 years old for Dumas and Wojtsuch (2018), Clauser et al. (1969) and Jensen (1986) study.

Anthropometric tables	Segments							
	Head and Neck	Trunk	Upper Arm	Lower Arm	Hand	Thigh	Shank	Foot
Dumas and Wojtsuch (2018) (%)	5.3	3.6	13.8	27.9	39.2	7.7	3.1	10
Clauser et al. (1969) (%)	1.8	24.5	8.3	32.7	6.8	19.9	3.4	1.4

Table 6. Mean relative difference of the transverse moment of inertia (radius of gyration in percentage of the segment length) for the foot and the hand old for males from 4 to 15 years old.

Study	Foot	Hand
Dumas and Wojtsuch (2018)	97.7±2.4%	137±0.6%
de Leva (1996)	5.8±1.3%	165±0.7%
Dempster (1955)	67±2%	25±0.7%
Chandler et al. (1975)	1.1±0.8%	99±0.5%

which was predictable because 15 years old is an age closest to the adult age, except for Dempster (1955) and Clauser et al. (1969). It can be explained by highest mean variabilities for the trunk, the hand and the foot at 15 years old than at 4 years old for both tables. The distal segments also present a higher relative difference for all the adults anthropometric tables compared to the other segments.

Table 7. Mean relative difference between the adults anthropometric tables and Jensen (1986) from 4 to 15 years old of the segment transverse moment of inertia, for all segments.

Anthropometric tables	Age (years)											
	4	5	6	7	8	9	10	11	12	13	14	15
Dumas and Wojtsuch (2018) (%)	32.4	32.5	32.6	32.6	32.7	32.8	32.9	33.0	33.1	33.2	33.3	33.4
de Leva (1996) (%)	28.3	28.4	28.5	28.5	28.6	28.6	28.7	28.7	28.8	28.8	28.9	28.9
Dempster (1955) (%)	20.2	20.4	20.6	20.8	21.1	21.3	21.5	21.7	21.9	22.2	22.4	22.7
Chandler et al. (1975)(%)	21.4	21.3	21.3	21.2	21.2	21.2	21.1	21.1	21.1	21.1	21.2	21.2

Table 8. Mean relative difference among all BSIPs between the adult anthropometric tables of Dumas and Wojtsuch (2018), Clauser et al. (1969) Chandler et al. (1975), Dempster (1955), de Leva (1996) and the Jensen (1986) study.

Anthropometric tables	BSIPs			
	Mass	Center of Mass	Transverse moment of inertia	Mean relative difference
Dumas and Wojtsuch (2018) (%)	22.24.2	13.9±0.5	33±0.3	23.0±9.5
Clauser et al. (1969) (%)	2.91.0	9.2±0.3	/	15.1±8.3 *
Chandler et al. (1975) (%)	31.411.7	17.0±1.7	21.0±0.1	23.1±7
Dempster (1955) (%)	2.41.6	11.3±0.2	21.4±0.8	17.7±5.6
de Leva (1996) (%)	23.03.5	11.2±0.4	28.6±0.2	20.9±8.9

Regarding the segment mass, the relative difference between the adults anthropometric tables and Jensen (1986) is decreasing from 4 to 15 years old,

For the segment CoM, the evolution of the position differs with the segments observed. The relative position of the CoM is decreasing for the shank and thigh while it

Table 9. Segment mass relative difference (in percentage %) for each segment, at each year and for each adult anthropometric table.

Anthropometric tables	4	5	6	7	8	9	10	11	12	13	14	15
Head												
Dumas and Wojtsuch (2018)	65.0	62.0	60.0	57.0	54.0	50.0	45.0	40.0	33.0	25.0	14.0	0.6
de Leva (1996)	63.0	61.0	58.0	56.0	52.0	48.0	43.0	38.0	31.0	22.0	11.0	4.0
Dempster (1955)	58.0	56.0	53.0	49.0	46.0	41.0	36.0	29.0	21.0	11.0	12.0	18.0
Clauser et al. (1969)	62.0	59.0	56.0	53.0	50.0	46.0	41.0	35.0	27.0	18.0	6.0	9.0
Chandler et al. (1975)	23.0	25.0	26.0	28.0	28.0	27.0	26.0	25.0	20.0	17.0	11.0	0.8
Trunk												
Dumas and Wojtsuch (2018)	16.0	15.0	14.0	12.0	11.0	10.0	8.0	7.0	5.0	3.0	2.0	0.4
de Leva (1996)	19.0	18.0	16.0	15.0	14.0	12.0	11.0	9.0	8.0	6.0	5.0	3.0
Dempster (1955)	17.0	18.0	20.0	22.0	24.0	26.0	28.0	30.0	33.0	35.0	37.0	40.0
Clauser et al. (1969)	25.0	27.0	29.0	31.0	33.0	35.0	37.0	39.0	42.0	44.0	47.0	50.0
Chandler et al. (1975)	22.0	25.0	28.0	31.0	34.0	37.0	39.0	43.0	45.0	48.0	52.0	55.0
Upper Arm												
Dumas and Wojtsuch (2018)	5.0	8.0	11.0	13.0	16.0	18.0	21.0	23.0	25.0	27.0	28.0	30.0
de Leva (1996)	6.0	3.0	0.2	2.0	5.0	8.0	10.0	13.0	15.0	17.0	19.0	21.0
Dempster (1955)	3.0	0.3	2.0	5.0	8.0	11.0	13.0	15.0	18.0	20.0	22.0	23.0
Clauser et al. (1969)	4.0	1.1	1.9	4.0	7.0	10.0	12.0	15.0	17.0	19.0	21.0	23.0
Chandler et al. (1975)	156	126	103	80.0	64.0	47.0	34.0	21.0	12.0	2.0	5.0	12.0
Lower Arm												
Dumas and Wojtsuch (2018)	10.0	9.0	7.0	6.0	5.0	4.0	3.0	1.9	0.8	0.1	1.2	2.2
de Leva (1996)	5.0	3.0	2.0	1.5	0.4	0.6	1.7	2.8	3.8	4.8	5.8	6.8
Dempster (1955)	0.5	0.5	1.0	2.8	3.9	4.9	6.0	7.0	8.0	8.9	9.9	10.8
Clauser et al. (1969)	4.0	3.0	2.0	0.9	0.1	1.2	2.3	3.4	4.4	5.4	6.4	7.4
Chandler et al. (1975)	81.0	67.0	57.0	4.07	39.0	31.0	24.0	17.0	13.0	8.2	3.5	0.1
Hand												
Dumas and Wojtsuch (2018)	32.0	32.0	31.9	31.5	31.3	31.0	30.9	30.8	30.3	30.0	29.9	29.6
de Leva (1996)	31.0	30.9	30.7	30.6	30.0	29.8	29.5	29.3	29.1	28.5	28.2	28.0
Dempster (1955)	32.0	32.0	31.8	31.0	31.3	31.0	30.0	30.5	30.2	30.1	29.0	29.6
Clauser et al. (1969)	26.0	26.0	26.0	25.8	25.0	25.3	25.0	24.7	24.6	24.3	24.0	23.7
Chandler et al. (1975)	41.0	38.0	36.0	34.0	33.0	31.0	29.0	28.0	27.0	26.2	25.0	24.2
Thing												
Dumas and Wojtsuch (2018)	52.0	45.0	39.0	33.0	28.0	24.0	19.0	15.0	11.0	8.0	4.0	1.7
de Leva (1996)	75.0	67.0	60.0	54.0	48.0	42.0	37.0	33.0	28.0	24.0	20.0	17.0
Dempster (1955)	19.0	14.0	10.0	5.0	1.6	2.1	5.5	8.8	11.0	14.0	17.0	19.0
Clauser et al. (1969)	26.0	21.0	16.0	11.0	7.0	3.0	0.003	3.0	6.0	9.0	12.0	15.0
Chandler et al. (1975)	70.0	57.0	49.0	41.0	36.0	31.0	27.0	24.0	23.0	21.0	20.0	20.0
Shank												
Dumas and Wojtsuch (2018)	11.0	8.0	5.0	2.9	0.3	2.1	4.5	6.8	8.9	11	12.9	14.0
de Leva (1996)	0.7	2.0	4.0	7.1	9.5	11.7	1.38	15.9	17.8	19.0	21.0	23.0
Dempster (1955)	4.7	1.8	0.9	3.4	5.9	8.2	10.5	12.6	14.6	16.0	18.0	20.0
Clauser et al. (1969)	1.2	1.5	4.2	6.7	9.0	11.3	13.5	15.0	17.0	19.0	21.0	22.0
Chandler et al. (1975)	13	7.6	2.6	2.1	6.1	10.0	13.0	16.0	19.0	22.0	24.0	26.0
Foot												
Dumas and Wojtsuch (2018)	37.0	38.0	38.7	39.0	39.6	40.1	40.0	41.0	41.4	41.8	42.3	42.7
de Leva (1996)	29.0	29.5	30.0	30.0	31.0	31.6	32.0	32.7	33.1	33.0	34.0	34.6
Dempster (1955)	27.0	28.0	28.5	29.1	29.6	30.0	30.6	31.2	31.7	32.2	32.6	33.0
Clauser et al. (1969)	23.0	24.0	25.0	25.5	26.0	26.6	37.0	27.7	28.2	28.8	29.3	29.8
Chandler et al. (1975)	49.0	35.0	24.0	14.0	6.0	1.5	8.4	15.0	19.0	24.0	29.0	32.0

is increasing for the other segments. Different factors can impact the result and one of them is puberty and how the body is growing during it. Indeed, according to Busscher et al. (2011) the extremities (hands and feet)

are the first to grow followed by the legs and the arms. It can be a possible explanation of the difficulties to compute BSIPs for the extremities and have an impact on the evolution of the CoM during the growth.

Table 10. Segment center of mass's relative difference (in percentage %) for each segment, at each year and for each adult anthropometric table.

Anthropometric tables	4	5	6	7	8	9	10	11	12	13	14	15
Head												
Dumas and Wojtsuch (2018)	8.2	7.7	7.1	6.6	6.1	5.5	5.0	4.5	4.0	3.5	3	2.5
de Leva (1996)	1.3	0.8	0.3	0.1	0.6	1.1	1.6	2.1	2.6	3.1	3.5	4.0
Dempster (1955)	14.6	14.3	13.7	13.2	12.6	12.0	11.5	11.0	10.4	9.9	9.3	8.8
Clauser et al. (1969)	4.3	3.8	3.3	2.7	2.2	1.7	1.2	0.7	0.2	0.1	0.6	1.1
Chandler et al. (1975)	34.0	33.0	33.0	32.0	31.7	31.0	30.0	29.7	29.1	28.5	27.9	27.3
Trunk												
Dumas and Wojtsuch (2018)	1.8	2.1	2.5	2.8	3.1	3.5	3.8	4.1	4.5	4.8	5.1	5.4
de Leva (1996)	16.6	16.2	15.8	15.4	15.0	14.6	14.2	13.9	13.5	13.1	12.7	12.3
Dempster (1955)	21.5	21.1	20.6	20.2	19.8	19.4	19.0	18.6	18.2	17.8	17.4	17
Clauser et al. (1969)	16.1	16.3	16.6	16.9	17.2	17.5	17.7	18.0	18.3	18.6	18.8	19.1
Chandler et al. (1975)	1.1	0.7	0.4	0.1	0.2	0.6	0.9	1.3	1.6	1.9	2.3	2.6
Upper Arm												
Dumas and Wojtsuch (2018)	13.6	13.6	13.7	13.8	13.8	13.9	13.9	13.9	13.98	14.0	14.1	14.1
de Leva (1996)	3.4	3.3	3.3	3.2	3.2	3.1	3.1	3.0	3.0	2.9	2.9	2.9
Dempster (1955)	21.8	21.9	21.9	21.9	22.0	22.1	22.1	22.2	22.2	22.2	22.3	22.3
Clauser et al. (1969)	8.0	8.1	8.2	8.2	8.3	8.3	8.4	8.4	8.5	8.5	8.5	8.6
Chandler et al. (1975)	8.0	8.1	8.1	8.2	8.2	8.3	8.3	8.4	8.4	8.4	8.5	8.5
Lower Arm												
Dumas and Wojtsuch (2018)	26.6	26.9	27.1	27.3	27.6	27.8	28.1	28.3	28.5	28.8	29.0	29.2
de Leva (1996)	19.5	19.8	20.0	20.3	20.6	20.8	21.1	21.3	21.6	21.9	22.15	22.4
Dempster (1955)	24.3	24.6	24.8	25.1	25.3	25.6	25.8	26.1	26.3	26.5	26.8	27.0
Clauser et al. (1969)	31.4	31.7	31.9	32.1	32.3	32.6	32.8	33.0	33.2	33.4	33.6	33.9
Chandler et al. (1975)	15.5	15.0	14.6	14.2	13.8	13.3	12.9	12.5	12.1	11.7	29.0	30.0
Hand												
Dumas and Wojtsuch (2018)	39.5	39.5	39.5	39.4	39.4	39.3	39.3	39.2	39.2	39.1	39.1	39.1
de Leva (1996)	31.9	31.3	31.3	31.3	31.2	31.2	31.1	31.1	31.1	31.0	31.0	30.9
Dempster (1955)	15.8	15.9	15.9	15.9	15.9	15.9	16.0	16.0	16.1	16.1	16.1	16.1
Clauser et al. (1969)	6.6	6.7	6.7	6.7	6.8	6.8	6.8	6.9	6.9	6.9	6.9	7.0
Chandler et al. (1975)	13.1	13.5	13.6	13.6	13.6	13.7	13.7	13.7	13.7	13.8	13.8	13.8
Thigh												
Dumas and Wojtsuch (2018)	8.9	8.7	8.5	8.2	8.0	7.8	7.6	7.3	7.1	6.9	6.6	6.4
de Leva (1996)	13.0	12.8	12.6	12.4	12.2	12.0	11.8	11.5	11.3	11.1	10.9	10.6
Dempster (1955)	8.1	7.8	7.6	7.4	7.2	6.9	6.7	6.5	6.2	6.0	5.8	5.5
Clauser et al. (1969)	21.0	20.8	20.6	20.4	20.2	20.1	19.9	19.7	19.5	19.3	19.1	18.9
Chandler et al. (1975)	17.6	17.4	17.2	17.0	16.8	16.6	16.4	16.2	15.9	15.7	15.5	15.3
Shank												
Dumas and Wojtsuch (2018)	6.7	6.0	5.4	4.7	4.1	3.4	2.7	2.0	1.3	0.6	0.1	0.8
de Leva (1996)	0.2	0.4	1.1	1.8	2.5	3.2	3.9	4.7	5.4	6.2	7.0	7.8
Dempster (1955)	1.7	1.0	0.3	0.3	1.0	1.7	2.4	3.1	3.9	4.6	5.4	6.2
Clauser et al. (1969)	0.5	0.1	0.7	1.4	2.1	2.9	3.6	4.3	5.1	5.8	6.6	7.4
Chandler et al. (1975)	18.0	19.0	20.0	20.0	21.0	22.0	23.0	24.0	25.0	26.0	27.0	27.8
Foot												
Dumas and Wojtsuch (2018)	13.4	12.9	12.4	12.0	11.5	11.1	10.6	10.1	9.7	9.3	8.8	8.4
de Leva (1996)	0.2	0.7	1.0	1.4	1.8	2.2	2.6	3.0	3.4	3.8	4.2	4.6
Dempster (1955)	3.0	3.4	3.8	4.2	4.6	5.0	5.4	5.8	6.2	6.5	6.9	7.3
Clauser et al. (1969)												
Chandler et al. (1975)	1.3	0.9	0.5	0.1	0.3	0.7	1.1	1.5	1.9	2.3	2.7	3.1
Dumas and Wojtsuch (2018)	27.0	26.0	26.0	25.7	25.2	24.6	24.2	23.7	23.1	22.6	22.2	21.6

For the segment transverse moment of inertia, the distal segments have the highest relative difference (foot

and head especially). The relative difference is higher for the females than for the males considering only Dumas

Table 11. Segment transverse moment of inertia's relative difference (in percentage %) for each segment, at each year and for each adult anthropometric table.

Anthropometric tables	4	5	6	7	8	9	10	11	12	13	14	15
Head												
Dumas and Wojtsuch (2018)	3.6	3.58	3.6	3.5	3.5	3.4	3.5	3.5	3.4	3.4	3.4	3.3
de Leva (1996)	2.6	2.6	2.6	2.6	2.5	2.5	2.5	2.5	2.5	2.4	2.4	2.4
Dempster (1955)	9.7	9.7	9.7	9.6	9.6	9.6	9.6	9.6	9.6	9.5	9.5	9.5
Chandler et al. (1975)	0.6	0.6	0.7	0.6	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.5
Trunk												
Dumas and Wojtsuch (2018)	9.7	9.8	10.0	10.2	10.4	10.5	10.7	10.9	11.1	11.2	11.4	11.6
de Leva (1996)	15.8	16.1	16.2	16.4	16.6	16.7	16.9	17.1	17.3	17.5	17.7	17.9
Dempster (1955)	30.6	30.8	31.0	31.2	31.4	31.6	31.81	32.0	32.2	32.4	32.7	32.9
Chandler et al. (1975)	7.7	7.6	7.5	7.3	7.2	7.1	6.9	6.8	6.6	6.5	6.3	6.2
Upper Arm												
Dumas and Wojtsuch (2018)	6.2	5.7	5.2	4.8	4.3	3.8	3.3	2.8	2.3	1.8	1.3	0.7
de Leva (1996)	7.8	7.3	6.9	6.4	5.9	5.4	5.0	4.5	4.01	3.51	3.0	2.5
Dempster (1955)	4.1	4.6	5.1	5.7	6.2	6.7	7.3	7.9	8.4	9.01	9.6	10.2
Chandler et al. (1975)	17.5	17	16.7	16.2	15.8	15.4	15	14.5	14.1	13.6	13.2	12.7
Lower Arm												
Dumas and Wojtsuch (2018)	3.5	3.2	3.0	2.7	2.4	2.2	1.9	1.7	1.4	1.1	0.8	0.5
de Leva (1996)	4.9	4.6	4.4	4.1	3.8	3.6	3.4	3.1	2.8	2.5	2.2	1.9
Dempster (1955)	4.3	4.6	4.9	5.2	5.5	5.7	6.1	6.3	6.7	7.0	7.3	7.6
Chandler et al. (1975)	34.0	34.0	34.7	35.0	35.5	35.8	36.2	36.5	37.0	37.4	37.8	38.2
Hand												
Dumas and Wojtsuch (2018)	135.0	135.0	135.9	136.1	136.3	136.5	136.7	136.9	137.0	137.2	137.4	137.6
de Leva (1996)	164.0	164.0	164.6	164.8	165.0	165.2	165.4	165.6	165.8	166.0	166.2	166.4
Dempster (1955)	24.0	25.0	25.1	25.2	25.3	25.4	25.5	25.6	25.7	25.8	25.9	26.0
Chandler et al. (1975)	97.0	97.8	98.0	98.2	98.3	98.4	98.6	98.8	98.9	99.1	99.3	99.4
Thing												
Dumas and Wojtsuch (2018)	7.0	7.2	7.5	7.78	8.0	8.3	8.5	8.8	9.1	9.4	9.6	9.9
de Leva (1996)	17.0	17.6	17.9	18.2	18.4	18.8	19.1	19.4	19.6	19.9	20.2	20.5
Dempster (1955)	15.0	15.4	15.7	16.1	16.3	16.6	16.9	17.2	17.5	17.8	18.0	18.3
Chandler et al. (1975)	3.4	3.6	3.9	4.2	4.4	4.7	4.9	5.2	5.5	5.7	5.9	6.2
Shank												
Dumas and Wojtsuch (2018)	0.2	8.6e-5	0.1	0.3	0.5	0.7	0.8	1.0	1.2	1.3	1.4	1.6
de Leva (1996)	10.0	10.3	10.5	10.7	10.8	10.9	11.1	11.3	11.4	11.5	11.7	11.8
Dempster (1955)	8.0	7.8	7.6	7.4	7.2	7.1	6.9	6.7	6.6	6.4	6.2	6.1
Chandler et al. (1975)	15.2	15.0	14.8	14.6	14.4	14.2	14.0	13.8	13.6	13.5	13.3	13.2
Foot												
Dumas and Wojtsuch (2018)	93.0	94.0	95.0	95.9	96.6	97.3	98.0	98.7	99.4	100.0	100.8	101.5
de Leva (1996)	3.0	4.2	4.5	4.9	5.2	5.6	6.0	6.4	6.7	7.1	7.5	7.8
Dempster (1955)	64.0	65.0	65.6	66.2	66.7	67.3	67.9	68.5	69	69.6	70.3	70.8
Chandler et al. (1975)	2.5	2.2	1.9	1.6	1.3	0.9	0.6	0.2	0.1	0.5	0.8	1.2

and Wojtsuch (2018) and de Leva (1996) studies. One can note that, it was important here to refer to the definition of the segment reference frame in which the segment transverse moment of inertia was computed, how the axis were described and from what segment endpoint it was defined.

There is no an adult anthropometric table that is close to the Jensen (1986) study for all BSIP. Dumas and Wojtsuch (2018) and Clauser et al. (1969) seem to be interesting in order to have a low relative difference on most of the segments. Moreover, the table of Dumas and

Wojtsuch (2018) is more complete as this study expresses each BSIP in function of the gender on contrary to Clauser et al. (1969).

One limit of this study is due to the chosen anthropometric tables studied here. Jensen (1986) was considered as our reference for the child anthropometric table and was compared to 5 specific adults anthropometric tables. The results cannot be generalised to others published anthropometric tables. Some of them only focus on certain BSIP and were not included in the comparison. Moreover, as previously

explained, most of the anthropometric tables considered here are based on males data and few of them consider females. Errors are introduced during the comparison between Jensen (1986) and Dumas and Wojtsuch (2018) for females data because Jensen (1986) only consider males data. Finally, this study includes anthropometric tables with different segment models and the comparison needed more computations and adjustments for gathering the different segments to obtain the trunk. Ongoing works will provide more comparisons of other BSIP parameters like segments length. Here, our study involves the main used anthropometric tables. However, other adults anthropometric tables can also be added to this comparison and see if different and better results can be obtained.

Finally, our results could also be extended to underweighted (Body Mass Index (*BMI*) < 18.5) and overweighted (*BMI* > 25) children. The results and the relative difference could be very different, particularly on the segment mass.

6. Conclusion

This study aims to quantify the relative difference for three BSIPs (transverse moment of inertia, center of mass along the supero-inferior axis and the mass) between some adults anthropometric tables and one children anthropometric table considered as our reference. The closest adult tables on comparable parameters could, in the future, be usefully reused to determine the missing anthropometric characteristics in the paediatric tables. Dempster (1955) has the lowest difference for the the segment mass, de Leva (1996) for the position of the CoM and Chandler et al. (1975) for the segment transverse moment of inertia over ages and for all segments. de Leva (1996) and Dumas and Wojtsuch (2018) are the most interesting tables to determine other paediatric parameters for each segment such as:

- products of inertia;
- moments of inertia (along the anterior-posterior axis and the medial-lateral axis);
- segments length;
- CoM defined along the anterior-posterior axis and the medial-lateral axis.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The data that support the findings of this study are openly available in the following repository at: <https://gitlab.laas.fr/sotmani/InternationalBiomechanics.git>.

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