DOES A NOVEL PROCEDURE FOR LIMITING MOTION AFFECT BODY COMPOSITION ESTIMATES BY DUAL-ENERGY X-RAY ABSORPTIOMETRY IN CHILDREN?

by

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A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Master of Science in Human Nutrition

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TABLE OF CONTENTS

LIST OF TABLES .................................................................................................................. vii

LIST OF FIGURES ................................................................................................................ viii

ABSTRACT ............................................................................................................................ ix

Chapter

1 INTRODUCTION

1.1. Introduction.................................................................1

1.2. Purpose.........................................................................3

1.3. Hypothesis.................................................................3

1.4. Significance.................................................................3

1.5. Limitations.................................................................4

2 LITERATURE REVIEW

2.1. Methods of body composition assessment.........................5

2.2. Body composition assessment in children and movement disorders......................................................... 10

2.3. Limiting subject motion during body composition assessment.................................................................15
JOURNAL MANUSCRIPT: DOES A NOVEL PROCEDURE FOR LIMITING MOTION AFFECT BODY COMPOSITION ESTIMATES BY DUAL-ENERGY X-RAY ABSORPTIOMETRY IN CHILDREN?

3.1. Abstract……………………………………………………………………..17
3.2. Introduction…………………………………………………………………19
3.3. Methods………………………………………………………………………20
  3.3.1. Participants and Protocol………………………………………………20
  3.3.2. Anthropometry………………………………………………………21
  3.3.3. Dual-energy X-ray Absorptiometry………………………………21
  3.3.4 Immobilization Using the BodyFIX…………………………………22
  3.3.5. Statistical Analysis……………………………………………………22
3.4. Results………………………………………………………………………..23
3.5. Discussion……………………………………………………………………24
3.6. Conclusion…………………………………………………………………27
3.7. References…………………………………………………………………28

4 SUMMARY AND CONCLUSION
4.1. Summary and conclusion…………………………………………………39

5 REFERENCES
5.1. References……………………………………………………………………40
### LIST OF TABLES

Table 1. Physical characteristics………………………………………………32

Table 2. Body composition estimates from dual-energy x-ray absorptiometry without
the BodyFIX, with the BodyFIX and with a modified version of the
BodyFIX…………………………………………………………………….....33

Table 3. Mathematical models for predicting fat mass and fat-free soft tissue mass
(FFST) from dual-energy X-ray absorptiometry (DXA) while using the BodyFIX
(BFIX) to immobilize 5 to 13 year-old
children………………………………………………………………….……..34
LIST OF FIGURES

Figure 1. Scatter plots and Bland-Altman plots showing relationship between total fat mass estimated by dual-energy x-ray absorptiometry (DXA) without the BodyFIX, with the BodyFIX and a modified version of the BodyFIX…………………………………………………………………….…….35

Figure 2. Scatter plots and Bland-Altman plots showing the relationship between total fat-free mass estimated by dual-energy x-ray absorptiometry (DXA) without the BodyFIX, with the BodyFIX and modified version of the BodyFIX……………………………………………………………………………36

Figure 3. Scatter plots and Bland-Altman plots showing the relationship between total bone mineral content estimated by dual-energy x-ray absorptiometry (DXA) without the BodyFIX, with the BodyFIX and with a modified version of the BodyFIX……………………………………………………………………………37

Figure 4. Scatter plots showing total fat mass and fat-free soft tissue mass estimated by dual-energy x-ray absorptiometry (DXA) using BodyFIX against body mass and body mass index (BMI)……………………………………………………………………………………..38
ABSTRACT

**Background:** Assessment of body composition is important in determining energy needs. This is particularly important in children with limited mobility and poor nutritional status such as children with cerebral palsy (CP). One of the most accurate methods for assessing body composition is dual-energy X-ray absorptiometry (DXA), but for children with difficulty controlling their movement, this can be difficult. The BodyFIX is a novel immobilization device that has been developed to limit motion during medical procedures and may allow for accurate assessment of body composition by DXA in children with movement disorders. However, no studies have tested the accuracy of body composition measurements by DXA when the BodyFIX is used to limit subject motion. **Purpose:** The purpose of this study was to determine if the BodyFIX can be used to limit the motion of children during a DXA scan without affecting the accuracy of total body soft tissue and bone mineral estimates. **Hypothesis:** It was hypothesized that using BodyFIX during a DXA scan would increase soft tissue mass and aBMD estimates in children. **Methods:** The subjects included twenty-five typically developing children (5-13 years). Total body fat mass (FM), fat-free soft tissue mass (FFST), body mass, bone mineral content (BMC), areal bone mineral density (aBMD) and bone area were determined by DXA without the BodyFIX, with the BodyFIX and with a modified version of the BodyFIX. The agreements between soft tissue and bone mineral estimates from DXA with and without the BodyFIX were assessed using linear regression analysis and Bland-Altman plots. The leave-one-out method
was used to determine the validity of the mathematical models developed to estimate soft tissue and bone mineral estimates from DXA while using the BodyFIX. **Results:** Total fat mass, FFST and body mass were overestimated (12.2%, 1.3% and 4.2%, respectively; \( p < 0.001 \)) when the full BodyFIX system was used to immobilize the children during the DXA scan. Despite the discrepancies, there were very strong relationships between soft tissue and bone estimates with the full BodyFIX compared to estimates without the BodyFIX \( (r^2 = 0.98, \ p < 0.001) \). Mathematical models developed to estimate total fat mass and FFST from DXA while using the full BodyFIX cross-validated very well \( (r^2 > 0.99) \). Furthermore, when the modified version of the BodyFIX was used to immobilize the children, the differences in total fat and FFST disappeared and the difference in body mass was substantially reduced. The differences in fat mass and body mass estimates with and without the full BodyFIX were positively related to body mass \( (r = 0.723, 0.825, \text{respectively, } p < 0.001) \) and body mass index \( (r = 0.637, 0.583, \text{respectively, } p < 0.01) \). **Summary and Conclusion:** The findings suggest that total fat mass and FFST by DXA are overestimated in children when the full BodyFIX is used to limit motion. However, the discrepancies can be corrected by mathematical models presented in the current study or avoided if a modified version of the BodyFIX is used. Future studies are needed to test the effectiveness of the BodyFIX at limiting motion during a DXA scan in children with movement disorders.
Chapter 1

INTRODUCTION

1.1. Introduction

Recommending appropriate nutritional intakes for children with movement disorders is difficult [1-4]. For example, recent population-based studies have shown that 30% to 40% of children with cerebral palsy (CP) are undernourished [5]. Conversely, others suggest that children with moderate to severe CP especially those who are tube-fed, may be experiencing overfeeding as demonstrated by excess adiposity [6]. In order to identify inappropriately nourished children and determine a suitable intervention, assessment of nutritional status is of prime importance. Body composition plays an important role in the assessment of nutritional status, disease risk, physical fitness and effectiveness of interventions [7]. Although validated equations have been developed for estimating height from segmented measures, and weight is readily measured [3, 8], the reliability of weight for height and body mass index to screen for inadequate fat stores has been questioned [9]. In addition, children with limited mobility have an altered body composition, with fat mass maintained more centrally as compared to able-bodied peers [9].

Multiple techniques exist for estimating body composition including hydrostatic weighing, hydrometry and 40K counting, isotope dilution, bioelectric impedance analysis (BIA), but these methods are limited in their accuracy, availability and suitability for all populations [10, 11]. Anthropometric measures, such as skin fold thickness, are readily
obtainable but they require equations developed against a “gold standard” method for translation into whole-body composition values. Furthermore, the accuracy of anthropometry-based body composition estimates are questionable in pediatric populations that may have altered fat distribution [1, 12].

Dual-energy x-ray absorptiometry (DXA) has made a significant advance as a method for evaluating body composition. In fact, some regard DXA as the gold standard for assessing body composition of children and adults [13-18]. Important features of DXA include excellent accuracy and precision, increasing availability, minimal radiation exposure, and short study time. Furthermore, regional estimates of body composition can be obtained and the body can be separated into three components (i.e., fat, fat-free soft tissue and bone mineral); whereas, the most common methods of body composition assessment only separate the body into two components (i.e., fat and fat-free mass).

There are limitations to the use of DXA in children with movement disorders such as CP. Children with CP often have joint contractures and spasticity, which prevent them from lying flat in the “anatomically correct” supine position. Although this decreases the reliability of body composition measures, good reliability is possible when scans are obtained in a position usually well tolerated by children with severe CP [19]. Another limitation of using DXA to estimate body composition in children with movement disorders is the uncontrolled movement that often occurs. A potential way to limit movement during a scan is to affix the children using BodyFIX, a novel immobilization system that uses a constant vacuum pressure to limit the motion of an individual. Studies in our laboratory show that immobilization using the BodyFIX is well tolerated by children with severe CP (32, 43, 45).
1.2. Purpose

The purpose of this study was to determine if the BodyFIX can be used to limit the motion of children during a DXA scan without affecting the accuracy of total body soft tissue and bone mineral estimates.

1.3. Hypothesis

It was hypothesized that using the BodyFIX during a DXA scan would increase soft tissue mass and aBMD estimates in children.

1.4. Significance

One of the most accurate methods for assessing body composition is dual-energy X-ray absorptiometry (DXA), but the involuntary movements experienced by many children with movement disorders, such as CP, make body composition assessment by DXA very difficult. The BodyFIX is a novel immobilization device that has been developed to limit motion during medical procedures and may allow for accurate assessment of body composition by DXA in children with movement disorders. However, no studies have tested the accuracy of body composition measurements by DXA when the BodyFIX is used to limit subject motion. If it is found that the BodyFIX has no effect on body composition estimates from DXA or if mathematical models can be developed to correct for errors introduced by the BodyFIX, it would support the use of the BodyFIX to limit motion of children during DXA scans.
1.5. Limitations

There are study limitations that should be mentioned. First, because the thickness of subjects was not assessed, the effect of body thickness on soft tissue, bone and body mass estimates from DXA when the BodyFIX was used cannot be tested with certainty. However, the differences between DXA estimates of total fat mass, FFST and body mass with and without the full BodyFIX were moderately to strongly related to body mass and BMI, suggesting that there are greater discrepancies in thicker individuals. Even if thickness altered the estimates of total fat mass and fat-free soft tissue mass (FFST), the mathematical models developed in the present study that estimate total fat mass and FFST from DXA using full BodyFIX system cross-validated extremely well using the leave-one-out method. Moreover, when a modified version of the BodyFIX was used to immobilize children, DXA estimates of total fat mass and FFST agreed very strongly with DXA estimates without the BodyFIX. A second limitation of the study is the age of the sample studied. It is possible the mathematical models developed would not be applicable to children outside of the 5 to 13 year-old age range to adults. A third limitation is that the mathematical models are limited to the type of DXA system and software used in the present study. DXA systems manufactured by different companies or different software version have been shown to yield different estimates of soft tissue mass and bone mass [20].
Chapter 2
LITERATURE REVIEW

The purpose of this section is to review: 1) methods of body composition assessment 2) body composition assessment in children and movement disorders and 3) limiting subject motion during body composition assessment

2.1. METHODS OF BODY COMPOSITION ASSESSMENT

The body is composed of protein, water, minerals and fat. The study of body composition involves the separation of body into different components according to elemental, chemical, anatomical or fluid components [21, 22] that, when taken together, make up a person’s body weight. The assessment of body composition has traditionally been based on the two-component model in which the body is divided into fat mass and fat-free mass. However, with advancement in utilization of technologies in body composition assessment, multi-component models have gained more widespread use [23, 24]. Body fat, the most variable constituent of the body consists of essential fat (found in the marrow of bones, heart, lungs, liver, spleen, kidneys, intestines, muscles, and lipid-rich tissues throughout the central nervous system) and storage fat [found around internal organs (internal storage fat) and directly beneath the skin (subcutaneous storage fat)]. The main function of subcutaneous fat is to provide the body with protection and serve as an insulator to conserve body heat.
Most methods of assessing body composition such as hydrostatic weighing, skinfolds and bioelectrical impedance analysis (BIA) are based on a two-component model [25]. Two-component model is based on the assumption that the body can be accurately separated into fat and fat-free components.

Until recently, hydrostatic weighing or underwater weighing was viewed as a criterion method of body composition assessment [26]. Hydrostatic weighing is based on principles promulgated by Archimedes, which states that when a body is submerged in water, there is a buoyant counter force equal to the weight of the water, which is displaced. Because bone and muscle are denser than water, a person with a larger percentage of fat-free mass will weigh more in the water. Because fat is less dense than water, a large amount of fat mass will make the body lighter in the water [27]. The accuracy of this method, if done correctly according to recommended guidelines, is approximately ± 2.7% in specific population groups [26] and ± 4% in the general population [28]. While not feasible for field studies, it is the approach that served as the gold standard for validating other methods until approximately 15 years ago [28-30]. One limitation of the hydrostatic weighing is that it is based on the two-component model, which assumes when calculating total body density that the relative amounts and densities of mineral, protein, and water comprising the fat-free mass are essentially the same for all individuals, regardless of age, gender, race, or fitness level. However, it has been shown that these assumptions are not accurate for some population groups. For example, compared to adults, children have lower mineral and more water in the fat-free mass [31, 32]. The result is lower density of the fat-free mass and the overestimation of percent body fat when adult equations are used. In
addition, the hydrostatic weighing is time consuming and requires a lot of equipment and space along with considerable experience to administer the tests. Being submerged under water may be difficult and produce anxiety for some.

The skinfold method of assessing body composition involves measuring the skinfold (subcutaneous fat) thickness at specific sites of the body. Seven- and three-site skinfold measurements are commonly used. The sites for the seven-site skinfold method include the chest, triceps, subscapular, axilla, suprailiac, abdomen and thigh. The sites for the three-site skinfold method include the chest, abdomen, and thigh for men and triceps, suprailiac and thigh for women. Most equations use the sum of at least three skinfolds to estimate body density from which body fat may be calculated [33]. The accuracy of this method, if done correctly according to recommended guidelines, is ± 4% in general population and ± 2.7% in specific population groups [25, 26, 34]. Although it is a quick and inexpensive method for assessing body composition, the accuracy of the skinfold method is dependent on the technician’s skill, as well as the type of caliper and skinfold prediction equation used.

Bioelectric impedance analysis (BIA) is based on the flow of electric current through the body’s intracellular and extracellular fluids. Since fat is a very poor conductor of electricity, fat impedes the current more so than lean tissue. By measuring the resistance to the current, the machine estimates body fat. The BIA technique is essentially an index of total body water, from which fat-free mass is estimated [35]. The BIA method has grown popular during the last two decades because it is painless, quick, and easy to administer. However, one drawback of BIA is
that it is relatively expensive and may not be an ideal method for obese and very lean individuals [1, 10, 11].

Development of various methodologies for estimation of the different components of the body has led to the emergence of multi-component models of body composition assessment. Dual-energy x-ray absorptiometry is based on a three-component model in which fat mass, fat-free soft tissue mass, and minerals are quantified. Dual-energy x-ray absorptiometry has made significant advance in the assessment of body composition. In fact, some regard it as a gold standard for assessing the body composition of children and adults [13-18]. Some of the important features of DXA include excellent accuracy and precision (< 1 – 2%), increasing availability, minimal radiation (1/10 of that for a chest radiograph), and short study time [36-38].

Several studies have attempted to validate body composition estimates from DXA against estimates from body density using a two-component model [39-42]. However, variation in the density of the fat-free mass (FFM) might lead to errors in body composition estimation from body density [43]. Body composition estimates from a four-component chemical model account for variation in the water and mineral fractions of the fat-free mass and therefore provides a better criterion measure for validating newer body composition methods [34]. A number of studies have used body composition estimates from a four-component chemical model to validate body composition estimates from DXA [36, 44-46].

Prior et al. [36] assessed the validity of whole body composition estimates from DXA against estimates from a four-component model to determine whether accuracy
is affected by gender, race, athletic status, or musculoskeletal development in young adults. Body density was measured by hydrostatic weighing, body water by deuterium dilution and bone mineral by whole body DXA in 172 young men (n = 91) and women (n = 81). There was no significant difference between methods [Mean of the difference ± SD of the difference = -0.4 ± 2.9 % body mass, p = 0.10]. A high correlation was found between percent body fat from DXA and percent body fat from the four-component model (r = 0.94, SEE = 2.8% body mass). Furthermore, when compared to percent body fat from the four-component model, percent body fat estimated from DXA was more accurate than percent body fat from body density (r = 0.9, SEE = 3.4%; mean of the difference ± SD of the difference = -1.2 ± 3.4% body mass). Differences between percent body fat measured by DXA and by the four-component model were weakly related to body thickness (r = -0.34) and to the percentage of water (r = -0.51) and thus it was concluded that the body composition estimates from DXA are accurate compared with those from a four-component model in young adults and are not affected by race, athletic status, musculoskeletal development or body fatness.

Wells et al. [23] evaluated interindividuality in the hydration, bone mineral content, and density of fat-free mass in children aged 8-12 years. The study also evaluated success with which two-component modes and other bedside techniques measured body composition in this age group with use of the four-component model as a reference. Body composition was determined using DXA, hydrostatic weighing, deuterium dilution, BIA, and anthropometry. Deuterium dilution and DXA did not show any mean bias for fatness compared with the four-component model. On the
other hand, hydrostatic weighing underestimated fatness (p < 0.025), and fatness measured by skinfold thickness and BIA showed poor agreement with the four-component model data. Thus, the findings demonstrate the accuracy of body composition estimates by DXA and the limitation of using other methods in children.

2.2. BODY COMPOSITION ASSESSMENT IN CHILDREN AND MOVEMENT DISORDERS

Evaluation of body composition is important in the assessment of growth and nutritional status in children. It is particularly important in the assessment of children with movement disorders such as chorea, dystonia and cerebral palsy (CP). Cerebral palsy is among the most common congenital disabilities associated with abnormal growth, body composition, physical activity and nutritional failure. It is caused by damage to one or more specific areas of the brain, usually occurring during fetal development, birth or during infancy. Children with CP are unable to fully control motor function, particularly muscle control and coordination contributing to low levels of physical activity [47]. Many of these children are also malnourished which leads to poor growth and reduced fat-free mass [2, 4, 6, 48]. Anthropometric measures of body fat (triceps and other skinfolds) indicate that body fat stores are reduced by 0.5 to 1 SD (between 25th and 10th percentiles) for children with quadriplegic CP and by about 0.3 SDs (between 25th and 50th percentiles) for children with less severe CP [2].

Some studies show that a significant part of the abnormal growth and body composition in children with spastic quadriplegic CP is directly attributable to poor nutritional status [2, 4, 48-50]. Stallings et al. [4] investigated the body composition
and nutritional status in a group of prepubertal children with spastic quadriplegic CP (n = 136) and compared them with healthy control children (n = 39). In addition to poor nutritional status, children with spastic quadriplegic CP had 25 % lower fat-free mass and 40 % lower fat mass than controls. Only moderate correlations were observed between fat mass from skinfolds measured at triceps, biceps, suprailiac, and subscapular sites and fat mass from total body water (r = 0.57 to 0.70, p<0.05).

In a second study, Stallings et al. [51] investigated the pattern of dietary intake, anthropometry and energy expenditure in a group of 61 spastic quadriplegic CP children aged 2-18 years and typically developing control children. Resting energy expenditure was determined using indirect calorimetry and total energy expenditure was determined using the doubly labeled water method. Physical activity, including spasticity, was estimated from the ratio of total energy expenditure to resting energy expenditure. Children with spastic quadriplegic CP were shorter and had lower body mass than controls. The children with CP and low fat stores had a lower resting energy expenditure adjusted for fat-free mass compared to children with CP and control children with adequate fat stores. Children with spastic quadriplegic CP also had lower total energy expenditure and a lower ratio of total energy expenditure to resting energy expenditure than the control group. They concluded that the nutrition-related growth failure and abnormal pattern of resting energy expenditure in children with spastic quadriplegic CP might be attributable to their inadequate energy intake.

Several studies have shown that children with quadriplegic CP have poor growth as indicated by low body mass and short stature [48, 52, 53]. This can be attributed to malnutrition because feeding dysfunction is common among these children [2],[54].
Chi-Keung et al. [55] evaluated the effect of feeding methods on growth in children with quadriplegic CP. One hundred nineteen typically developing children and 62 orally fed and 48 tube-fed children with quadriplegic CP participated in the study. Height, weight, skinfold thickness and arm circumference were measured. Weight-for-height z scores of the orally fed children with CP were significantly below those of typically developing children and tube-fed children with CP. For children with CP, there was a good correlation (r = 0.86) between triceps skinfold thickness measured by calipers and mid-upper arm fat area. Also, there was a negative correlation between presence of CP and thigh and calf fat areas (partial correlation = -0.45 and -0.53, respectively). The authors concluded that skinfold thickness may overestimate the fat area in the affected limb with significant muscle wasting for children with CP, which might be one of the reasons for low weight-for-height among these children.

In a cross-sectional study of 59 children with spastic quadriplegic CP, Arrowsmith et al [56] evaluated whether skinfold thickness, anthropometry and DXA could predict body protein. Measurements of height, weight, and lean tissue mass by DXA and total body protein by neutron activation analysis were estimated. In addition, the total body protein was also estimated from both skinfold thickness and DXA. Children with spastic quadriplegic CP had low height and weight SD scores (-3.1 ± 1.6 and –4.8 ± 5.3 respectively) along with low total body protein from neutron activation analysis for age and height (p < 0.001; 56.1 ± 17.3% and 81.5 ± 15.7%, respectively, of the predicted values). Although agreement analysis showed a wide variation (of up to 33.3% of the mean for both DXA and skinfold anthropometry), total body protein from skinfold and DXA were strongly correlated with total body
protein from neutron activation analysis (r = 0.90 and r = 0.91, respectively, p<0.001). Thus it was concluded that both DXA and skinfold measures could be used as indicators of body protein in children with spastic quadriplegic CP but with caution.

The isotope dilution technique measures the water compartment of the whole body rather than a single area. It is ideal for people with CP because it is noninvasive, it does not require the subject to remain still for the measurement and it is independent of height and body symmetry. Hildreth et al [57] studied the accuracy of body composition estimates from DXA, BIA, and skinfold anthropometry using the $^{18}$O isotope dilution technique as the criterion method in adults (20-55 years) with CP. The most favorable agreement was between DXA and $^{18}$O as there was no significant difference between percent body fat estimated by the two methods and the limits of agreement were smaller (mean difference ± limits of agreement: 0.06 ± 9.6 %) than when percent body fat from $^{18}$O was compared to percent body fat from skinfold thickness (mean difference ± limits of agreement: 6.33 ± 12.3%) and BIA (mean difference ± limits of agreement: -6.55 ± -13.6%). The findings demonstrate the greater accuracy of predicting percent body fat by DXA vs. other commonly used methods in individuals with CP.

Children with CP often have joint contractures or other deformities that prevent them from lying flat in the anatomical position. Henderson et al. [19] evaluated the effect of “poor” positioning on the assessment of body composition with DXA. The sample included thirty-seven normal children (3-16 years). Multiple whole body scans were performed: two in positions typical of children with contractures (frog-leg supine, semilateral) and one in full lateral supine position. Positions simulating
children with contractures showed mean errors of 4-6% for bone mineral content, 1-3%
for lean body mass and 5-11% for the fat mass. Strong correlations were observed
between body composition measures in the correct fully supine position and the
contracted position. The authors concluded that precise and accurate measures of body
composition could be obtained with DXA in children with deformities that preclude
fully supine positioning.

Another factor that could limit the accuracy of body composition estimates by
DXA is involuntary muscle contractions experienced by many children with CP.
Motion artifacts limit measurement accuracy [58-61] and lead to unpredictable
alterations in fat mass, FFST and BMC estimates by DXA [61]. Koo et al [58] studied
various conditions to determine the clinical and experimental parameters that may
interfere with DXA-based BMC and BMD measurements. Variations in data
acquisition included covering of external calibration standard with cotton blanket or
partial exclusion of the external calibration standard in the scan field, tissue freezing,
and presence of small nonmetallic objects, movement artifacts, radiographic contrast
media and nonmetallic orthopedic casts. The average coefficient of variation was
noted to be 2.9% and 1% for BMC and BMD measurements, respectively. In addition,
manual delineation of external calibration standard during data analysis led to
approximately 30% difference in DXA- BMC and BMD. In a similar study, the same
authors [59] studied 35 infants weighing 2115 to 11564 g and ages between 10 h to
365 h to determine the effect of subject movement during data acquisition. Analysis of
29 pairs of scans (one scan with and another scan without motion artifact) showed
increased DXA bone measurement along with increased values for fat mass and lean
mass measurements (p < 0.05). Cawkwell et al [61] studied the effect of various simulated movements on assessment of DXA fat mass, lean mass and BMC. Eleven adults were scanned five times with simulated movements (slow horizontal movements, fast horizontal movements, isolated movements of extremities and head, and slow vertical movements) that may occur in the clinical setting. In addition, 90 sequential DXA scans were retrospectively reviewed to assess the frequency and causes of movements during DXA scanning. The results demonstrated presence of movement in 23% of 90 sequential DXA scans. There was no difference in percent of subjects (age wise) that moved during DXA scanning. In addition, presence of movement resulted in unpredictable alteration in the assessment of BMC, lean mass and fat mass.

2.3. LIMITING SUBJECT MOTION DURING BODY COMPOSITION ASSESSMENT

If motion during DXA scans is limited, the reliability and accuracy of body composition assessment can be improved in children that have difficulty holding still. The BodyFIX is a novel immobilization device that has been developed to limit motion during medical procedures [62] and may allow for accurate assessment of body composition by DXA in children that have difficulty limiting their movement. To date, no studies have used the BodyFIX to immobilize the children during a DXA scan; however, it has been used to successfully limit motion during other imaging procedures. For instance, the BodyFIX has been used to immobilize children with severe cerebral palsy during magnetic resonance imaging and
assessment of muscle and adipose tissue cross-sectional area in the thigh [63], cortical bone structure in the mid femur [64] and trabecular bone microarchitecture in the distal femur [65].
Chapter 3

JOURNAL MANUSCRIPT: DOES A NOVEL PROCEDURE FOR LIMITING MOTION AFFECT BODY COMPOSITION ESTIMATES BY DUAL-ENERGY X-RAY ABSORPTIOMETRY IN CHILDREN?

3.1. Abstract

Assessing body composition in children with movement disorders can be difficult using dual-energy-x-ray absorptiometry (DXA). One promising method to limit motion during DXA scans is the BodyFIX; however, whether it affects the accuracy of body composition estimates by DXA has not been determined. The purpose of the study was to determine if the BodyFIX can be used to limit the motion of children during a DXA scan without affecting the accuracy of total body soft tissue and bone mineral estimates. The subjects included twenty-five typically developing children (5-13 years). Total body fat mass, fat-free soft tissue mass (FFST), body mass, bone mineral content (BMC), areal bone mineral density (aBMD) and bone area were determined by DXA without the BodyFIX, with the BodyFIX and with a modified version of the BodyFIX. The agreements between soft tissue and bone mineral estimates from DXA with and without the BodyFIX were assessed using linear regression analysis and Bland-Altman plots. The leave-one-out method was used to determine the validity of the mathematical models developed to estimate soft tissue and bone mineral estimates from DXA while using the BodyFIX. Total fat mass, FFST and body mass were overestimated when the full BodyFIX system was used to immobilize the children during the DXA scan. Despite the discrepancies, there were very strong relationships between soft tissue and
bone estimates with the full BodyFIX compared to estimates without the BodyFIX ($r^2 = 0.98$, $p < 0.001$). Mathematical models developed to estimate total fat mass and FFST from DXA while using the BodyFIX cross-validated very well ($r^2 > 0.99$).

Furthermore, when the modified version of the BodyFIX was used to immobilize the children, the differences in total fat and FFST disappeared and the difference in body mass was substantially reduced. The differences in fat mass and body mass estimates with and without the full BodyFIX were positively related to body mass ($r = 0.723$ and $0.825$, respectively, $p < 0.001$) and body mass index ($r = 0.637$ and $0.583$, respectively, $p < 0.01$). The findings suggest that total fat mass and FFST by DXA are overestimated in children when the full BodyFIX is used to limit motion. However, the discrepancies can be corrected by mathematical models presented in the current study or avoided if a modified version of the BodyFIX is used.
3.2. Introduction

Body composition plays an important role in the assessment of growth, nutritional status, disease risk and physical fitness [1, 2]. Clinicians and researchers are, however, hampered by the complexities of evaluating body composition in children, especially those with movement disorders such as cerebral palsy, muscular dystrophy, and dystonia. The accuracy of anthropometry-based estimates of body composition in children with movement disorders has been questioned [3]. Moreover, most body composition techniques do not provide regional estimates of body composition. This is important because children with movement disorders have a greater degree of central adiposity than typically developing children [4] which is strongly associated with chronic disease risk [5, 6].

Dual-energy x-ray absorptiometry (DXA) has made significant advance as a body composition method. In fact, some regard DXA as the gold standard for assessing body composition of children and adults [7-12]. Important features of DXA include excellent accuracy and precision, increasing availability, minimal radiation exposure and short study time. Furthermore, regional estimates of body composition can be obtained and the body can be separated into three components (i.e., fat mass, fat-free soft tissue and bone mineral); whereas the most common methods of body composition assessment only separate the body into two components (i.e., fat and fat-free mass).

There are limitations to the use of DXA in children. For instance, assessment of body composition in children with movement disorders such as cerebral palsy can be very difficult or even impossible as these children often have joint contractures and
spasticity that prevent them from lying flat in the “anatomically correct” supine position. Moreover, the uncontrolled movement that often occurs due to involuntary muscular spasms makes body composition assessment by DXA very difficult. Movement artifacts limit measurement accuracy [13-15] and lead to unpredictable alterations in the assessment of fat mass, fat-free soft tissue mass (FFST) and bone mineral content (BMC) [2]. A potential way to limit movement during a scan is to affix the children with movement disorders using the BodyFIX, a novel immobilization system that uses a constant vacuum pressure to limit the motion during medical procedures. However, the effect of the BodyFIX on body composition estimates by DXA is unknown. It is possible that the added material or the added thickness introduced by the BodyFIX system increases the body mass and alters the body composition estimates by DXA.

The purpose of this study was to determine if the BodyFIX can be used to limit motion of children during a DXA scan without affecting the accuracy of total body soft tissue and bone mineral estimates. It was hypothesized that using the BodyFIX during a DXA scan would increase soft tissue mass and aBMD estimates in children.

3.3. Methods

3.3.1. Participants and Protocol

Typically developing children between 5 and 13 years of age were recruited from the Newark, DE community using flyers. Procedures followed were in accordance with the ethical standards of institutions on human experimentation. The
study was approved by the Institutional Review Board at the University of Delaware. Subjects’ parents provided written consent and subjects provided written assent before testing was initiated. All testing was completed during a single session that lasted approximately 60 minutes.

3.3.2. Anthropometry

Body mass was measured to the nearest 0.1 kg using a double-beam balance scale (Health O Meter; Continental Scale Corp., Bridgeview, IL). Height was measured to the nearest 0.1 cm using a stadiometer fixed against a wall (SHORR Productions, Woonsocket, RI).

3.3.3. Dual-energy X-ray Absorptiometry

Fat mass, FFST, percent body fat, BMC, areal bone mineral density and bone area of the total body was assessed four times using dual-energy X-ray absorptiometry (DXA; Delphi W; Hologic, Inc). Each scan lasted approximately seven minutes. Two scans were conducted using the standard scanning procedure. Two scans were conducted while the subject was immobilized from the waist down using the BodyFIX. One of the two scans involved a modified version of the BodyFIX in which the blue bag was not used to assist in immobilizing the subjects. Quality control was checked before each scan by scanning a lumber spine phantom consisting of calcium hydroxyapatite embedded in a cube of thermoplastic resin (model DPA/QDR-1; Hologic x-caliber anthropometric spine phantom). To ensure consistency, one trained technician performed all tests.
3.3.4. Immobilization using the BodyFIX

The BodyFIX (Medical Intelligence, Inc., Schwabmunchen, GER) consisted of:
1) a large deflatable cushion (i.e., blue bag) that the subject lies on in the supine position when the air was removed using a vacuum system; 2) a plastic-like foil that was placed over the subject while on the large deflatable cushion; 3) smaller stabilizing cushions placed around the subject that minimized movement around the waist and extremities; and 4) a vacuum that drew air from the space between the foil and the subject, which hardened the stabilizing cushions and created a constant pressure on the subject’s waist and lower extremities. For the modified version of BodyFIX procedure, the blue bag was not used.

3.3.5. Statistical Analysis

Data were analyzed using SPSS version 16.0 (Chicago, IL). A one-way analysis of variance was used to compare DXA estimates of body composition (i.e., total fat mass, FFST, body mass, BMC, aBMD and bone area) with the full BodyFIX, with a modified version of the BodyFIX and without the BodyFIX. Linear regression analysis and Bland-Altman plots were used to determine the agreement between estimates of body composition with and without the BodyFIX. Pearson correlation analysis was used to determine the relationship between the difference in body composition and body mass estimates with and without the BodyFIX and markers of body size/thickness (i.e., total, body mass and BMI). Mathematical models developed using linear regression analysis were cross-validated for estimates of total fat mass and FFST using the leave-one-out method [16].
3.4. Results

Twenty-five children (13 boys and 12 girls) participated in the study. The descriptive characteristics of the sample are shown in Table 1. Height, body mass and body mass index (BMI) averaged between the 62\textsuperscript{nd} and the 65\textsuperscript{th} percentiles.

Body composition estimates from DXA are summarized in Table 2. When the full BodyFIX system was used to immobilize the children during the DXA scan, total fat mass, FFST and body mass were overestimated by 12.2 \%, 1.3 \% and 4.2 \% respectively (p < 0.001), and total body percent fat was overestimated by 2.2 ± 1.0 percentage points (p < 0.001). When a modified version of the BodyFIX was used to immobilize the children (i.e., without the deflatable blue bag), none of the body composition estimates were significantly different from estimates without the BodyFIX (p > 0.05). Although total body mass from DXA was overestimated when the modified version of the BodyFIX was used during the scan, the overestimation was very small (167 g or 0.5 \%, p = 0.006).

Scatter plots in Figures 1, 2 and 3 demonstrate the very strong relationships between DXA estimates of body composition with and without the BodyFIX ($r^2 \geq 0.98$ for all measures). The relationships were equally strong irrespective of the BodyFIX method (i.e., with or without the blue bag); however, the overestimation of total fat mass and the slight overestimation of FFST when the full BodyFIX was used is demonstrated by the regression line below the line of identity. The overestimation of total fat mass and FFST and close agreement of BMC when the full BodyFIX was used is further demonstrated by the Bland-Altman Plots in Figure 1, 2 and 3. The improved agreement between total fat mass and FFST estimates when the modified
version of the BodyFIX was used vs. not used is further demonstrated by the regression line falling on top of the lines of identity and the fat mass and FFST differences consistently near the zero line across the range of total fat mass and FFST.

The differences in total fat mass and body mass between DXA with and without the full BodyFIX were positively related to body mass (r = 0.723 and 0.825, respectively, p < 0.001) and BMI (r = 0.637 and 0.583, respectively, p < 0.01). Although total fat mass, FFST and body mass from DXA were overestimated in all subjects when the full BodyFIX system was used during the DXA scan, these relationships suggest that the overestimation was greater in larger, thicker subjects. This is demonstrated by the scatter plots in figure 4.

Mathematical models developed to correct for the overestimation of total body fat mass and FFST when the BodyFIX was used are reported in Table 3. The leave-one out cross-validation analysis indicated very strong agreement between predicted fat mass and FFST and fat mass_{DXA-STD} and FFST_{DXA-STD}, respectively.

3.5. Discussion

The purpose of study was to determine if using the BodyFIX to limit motion during a DXA scan affects the accuracy of body composition estimates in children. The major finding was that total fat mass and FFST were overestimated when the full BodyFIX system was used. However, accurate estimates resulted when appropriate prediction equations were applied. Accurate estimates of body composition from DXA also resulted when a modified version of the BodyFIX was used to limit motion.
It was hypothesized that using the BodyFIX during a DXA scan would increase soft tissue mass and aBMD estimates in children. One potential reason for the overestimation of fat mass and FFST when the full BodyFIX was used to limit motion was the additional material included in the DXA scan (i.e., blue bag, stabilizing cushions, plastic sheet and plastic tubing). A study by Koo et.al. [13] found that the inclusion of a cotton blanket and/or a diaper when scanning infants increased estimates of FFST and body mass (p < 0.001). The BodyFIX includes a 4545 g blue pillow that the subject lies on and creates a mold around the subject when the air is removed. It also includes a plastic foil along with stabilizing cushions to cover subjects’ body to minimize movement during the X-ray procedure, which have a combined mass of 1023 g. Interestingly, when all of the additional materials from the BodyFIX were included in the DXA scan, only ~25 % of the actual mass of the material was added to total body mass estimates. When the blue bag was removed from the scanning region using a modified version of the BodyFIX, there was no longer an overestimation of total fat mass and FFST and body mass was overestimated by only 0.5 %.

It is unlikely that the inclusion of additional material in the DXA scanning region was the only contributor to the increase in total fat mass and FFST when the full BodyFIX was used to limit subject motion. Previous studies by Laskey et.al and Jebb et.al [17, 18] have shown that subject thickness could influence body composition measures, especially fat mass and bone. Both studies used in vitro simulations (i.e., water to represent fat-free soft tissue mass and oil or lard to represent fat mass) to document the systematic effect of increasing tissue thickness. Laskey et.al [17] reported
that body thickness both less than 20 cm and greater than 20 cm leads to errors and imprecision in body composition measures with a greater effect at higher than lower thickness. Body thickness less than 20 cm leads to fat mass overestimation by only 4 % or less and FFST overestimation by 2 % or less, but this overestimation increased with increasing body thickness. Jebb et.al [18] also reported similar findings and concluded that tissue thickness both thick and thin may lead to overestimation of fat mass. Laskey et.al and Jebb et.al.[17, 18] have also investigated the effect of subject thickness on aBMD estimates, reporting an increase of about 2 % with an increase in subject thickness up to 28 cm. In the present study, however, the BodyFIX did not have a detectable effect on total body BMC, aBMD or bone area estimates by DXA.

To our knowledge, no studies have used the BodyFIX to immobilize children with movement disorders during a DXA scan, but the BodyFIX has been used to immobilize children during other imaging procedures. For instance, the BodyFIX has been used to immobilize children with severe cerebral palsy during magnetic resonance imaging and assessment of muscle and adipose tissue cross-sectional area in the thigh [19], cortical bone structure in the mid femur [20] and trabecular bone microarchitecture in the distal femur [21]. Future studies are needed to determine if the procedure is effective at holding children still during a DXA scan.

There are study limitations that should be mentioned. First, because the thickness of subjects was not assessed, the effect of body thickness on soft tissue, bone and body mass estimates from DXA when the BodyFIX was used cannot be tested with certainty. However, the differences between DXA estimates of total fat mass, FFST and body mass with and without the full BodyFIX were moderately to strongly related to body mass and
BMI suggesting that there are greater discrepancies in thicker individuals. Even if thickness altered the estimates of total fat mass and FFST, the mathematical models developed in the present study that estimate total fat mass and FFST from DXA using the full BodyFIX system cross-validated extremely well using the leave-one-out method (Table 3). Moreover, when a modified version of the BodyFIX was used to immobilize children, DXA estimates of total fat mass and FFST agreed very strongly with DXA estimates without the BodyFIX. A second limitation of the study is the age of the sample studied. It is possible the mathematical models developed would not be applicable to children outside of the 5 to 13 year-old age range of the children in the present study or to adults. A third limitation is that the mathematical models are limited to the type of DXA system and software used in the present study. DXA systems manufactured by different companies or different software version have been shown to yield different estimates of soft tissue mass and bone mass [22].

3.6. Conclusion

In conclusion, total fat mass, FFST and body mass were overestimated when the full BodyFIX was used to immobilize children during a DXA scan. The discrepancies were positively related to the size of the subject. Despite the errors, mathematical models to estimate total fat mass and FFST were developed and cross-validated using the leave-one-out technique. Accurate estimates of total fat mass and FFST were also achieved by using a modified version of the BodyFIX in which the blue bag is not included in the procedure. Future studies are needed to test the effectiveness of the BodyFIX at limiting motion during a DXA scan in children with movement disorders.
3.7. References


Table 1. Physical characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>(n = 25)</td>
<td></td>
</tr>
<tr>
<td>Age (y)</td>
<td>8.9 ± 2.5</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.38 ± 0.20</td>
</tr>
<tr>
<td>Height percentile</td>
<td>65 ± 23</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>34.1 ± 13.1</td>
</tr>
<tr>
<td>Body mass percentile</td>
<td>65 ± 25</td>
</tr>
<tr>
<td>Body mass index (kg/m²)</td>
<td>18.1 ± 3.80</td>
</tr>
<tr>
<td>Body mass index percentile</td>
<td>62 ± 29</td>
</tr>
</tbody>
</table>
Table 2. Body composition estimates from dual-energy x-ray absorptiometry (DXA) using the standard procedure, with the BodyFIX and with modified version of the BodyFIX

<table>
<thead>
<tr>
<th>Variables</th>
<th>Standard</th>
<th>BodyFIX</th>
<th>Modified BodyFIX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fat mass (kg)</td>
<td>10.1 ± 7.1</td>
<td>11.9 ± 7.7*</td>
<td>10.1 ± 7.0</td>
</tr>
<tr>
<td>FFST (kg)</td>
<td>23.4 ± 7.9</td>
<td>24.7 ± 9.0*</td>
<td>23.5 ± 8.1</td>
</tr>
<tr>
<td>Body mass(kg)</td>
<td>34.7 ± 1.4</td>
<td>37.8 ± 1.5*</td>
<td>34.8 ± 1.4</td>
</tr>
<tr>
<td>%Fat</td>
<td>27.2 ± 8.7</td>
<td>29.7 ± 8.4*</td>
<td>27.2 ± 8.3</td>
</tr>
<tr>
<td>BMC (g)</td>
<td>1210 ± 443</td>
<td>1260 ± 472</td>
<td>1213 ± 449</td>
</tr>
<tr>
<td>aBMD (g/cm²)</td>
<td>0.759 ± 0.091</td>
<td>0.768 ± 0.092</td>
<td>0.757 ± 0.092</td>
</tr>
<tr>
<td>Bone area</td>
<td>1561 ± 407</td>
<td>1605 ± 429</td>
<td>1567 ± 410</td>
</tr>
</tbody>
</table>

*Different from the standard DXA values without the BodyFIX, p < 0.001.

FFST = Fat-free soft tissue mass, BMC = Bone mineral content, aBMD = areal Bone mineral density
Table 3. Mathematical models for predicting fat mass and fat-free soft tissue mass (FFST) from dual-energy X-ray absorptiometry (DXA) while using the BodyFIX (BFIX) to immobilize 5 to 13 year-old children

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Model</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fat(_{DXA-STD}) (g)</td>
<td>Fat(_{DXA-BFIX}) (g) * 0.946 - 555</td>
<td>(r^2 = 0.997), SEE = 124 g</td>
</tr>
<tr>
<td>FFST(_{DXA-STD}) (g)</td>
<td>FFST(_{DXA-BFIX}) (g) * 0.982 + 129</td>
<td>(r^2 = 0.999), SEE = 188 g</td>
</tr>
</tbody>
</table>

Fat\(_{DXA-STD}\) and FFST\(_{DXA-STD}\) = fat mass and fat-free soft tissue mass, respectively, from DXA using the standard procedure without the BodyFIX; both models are statistically significant, \(p < 0.001\).
Figure 1.

Scatter plots show the relationship between total fat mass estimated by dual-energy x-ray absorptiometry (DXA) using the standard procedure without the BodyFIX (Fat\text{STD}) and total fat mass estimated by DXA using the BodyFIX (Fat\text{BFIX}; A) and between Fat\text{STD} and total fat mass estimated by DXA using a modified version of the BodyFIX (Fat\text{ModiBFIX}; B). Bland-Altman plots show the overestimation of Fat\text{STD} by Fat\text{BFIX} (C) and closer agreement between Fat\text{STD} and Fat\text{ModiBFIX} (D). The dotted line is the line of identity. The solid line is the regression line.
Figure 2.

Scatter plots show the relationship between total fat-free soft tissue mass estimated by dual-energy x-ray absorptiometry (DXA) using the standard procedure without the BodyFIX (FFST\textsubscript{STD}) and FFST estimated by DXA using the BodyFIX (FFST\textsubscript{BFIX}; A) and between FFST\textsubscript{STD} and FFST estimated by DXA using a modified version of the BodyFIX (FFST\textsubscript{ModiBFIX}; B). Bland-Altman plots show the slight overestimation of FFST\textsubscript{STD} by FFST\textsubscript{BFIX} (C), and closer agreement between FFST\textsubscript{STD} and FFST\textsubscript{ModiBFIX} (D). The dotted line is the line of identity. The solid line is the regression line.
Figure 3.

Scatter plots show the relationship between total bone mineral content estimated by dual-energy x-ray absorptiometry (DXA) using the standard procedure without BodyFIX (BMC_{STD}) and total BMC estimated by DXA using the BodyFIX (BMC_{BFIX}; A) and between BMC_{STD} and total BMC estimated by DXA using a modified version of the BodyFIX (BMC_{ModiBFIX}; B). Bland-Altman plots show the agreement between BMC_{STD} and BMC_{BFIX} (C) and between BMC_{STD} and BMC_{ModiBFIX} (D). The dotted line is the line of identity. The solid line is the regression line.
Figure 4.

Scatter plots show the relationship between the difference in fat mass by dual-energy x-ray absorptiometry (DXA) without the BodyFIX (Fat\textsubscript{STD}) and with the BodyFIX (Fat\textsubscript{BFIX}) and body mass (A), between the difference in Fat\textsubscript{STD} and Fat\textsubscript{BFIX} and body mass index (BMI; B), between the difference in fat-free soft tissue mass by DXA without the BodyFIX (FFST\textsubscript{STD}) and with the BodyFIX (FFST\textsubscript{BFIX}) and body mass (C), and between the difference in FFST\textsubscript{STD} and FFST\textsubscript{BFIX} and BMI (D). The dotted line indicates no difference. The solid line is the regression line.
Chapter 4

SUMMARY AND CONCLUSION

4.1. Summary and conclusion

Excess movement during a DXA scan can create error in body composition estimates. This is a particular problem in children with movement disorders, such as CP. To our knowledge, no studies have used the BodyFIX to immobilize children with movement disorders during a DXA scan; however, the BodyFIX has been used to immobilize children during other imaging procedures. The present study showed that total fat mass, FFST and body mass are overestimated when the full BodyFIX is used to immobilize children during a DXA scan. The discrepancies were positively related to the size of the subject. Despite the errors, mathematical models to estimate total fat mass and FFST were developed and cross-validated using the leave-one-out technique. Furthermore, the overestimates of fat mass and FFST were no longer present when a modified version of the BodyFIX was used during a DXA scan.

It is concluded that the BodyFIX can be used to immobilize 5 to 13 year old children during a DXA scan if the proposed mathematical models or a modified version of the BodyFIX are used. Future studies are needed to test the effectiveness of the BodyFIX at limiting motion during a DXA scan in children with movement disorders.
Chapter 5

REFERENCES


