2016

Differences in Running Mechanics Between Overweight/Obese and Healthy Weight Children

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DIFFERENCES IN RUNNING MECHANICS BETWEEN OVERWEIGHT/OBESE AND HEALTHY WEIGHT CHILDREN

BY

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A thesis submitted in partial fulfillment of the requirements for the

Master of Science

Major in Nutrition and Exercise Science

Specialization in Exercise Science

South Dakota State University

2016

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This thesis is approved as a creditable and independent investigation by a candidate for the Master Science in Nutrition, Exercise, and Food Sciences degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidates are necessarily the conclusions of the major department.

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ACKNOWLEDGEMENTS

This is for anyone who helped influence me in the biggest or smallest of ways. With every passing day we encounter a number of people who will change our lives in one way or another. While the life of a Master's student is not always glorious, the people who helped me get to this point have been glorious in their own special ways.

- To my grad school friends: you have accepted and embraced me in a way that only a family could, and through our experience, family is what we have become. You have become some of the most important people in my life. Thank you for always knowing when I need a good laugh, and a free cookie!
- To my teachers, coaches, and mentors: there once was a time when I did not know if college was for me. Looking back on my journey, I know that without your endless encouragement and confidence my life would be completely different in so many ways. I thank you for always pushing me to my limits and knowing that those limits are much further than I know.
- To Dr. Bowser: It is hard for me to even put into words the influence you have had on me these past few years. You have exposed me to a whole new world and helped me become someone that I can be proud of. You have always been someone I can count on and have helped keep me stable through this process. First, I must thank you for understanding the right moments of when to push me and when it was too much. Second, thank you for being more than just an advisor to me academically. You have taught me so many life lessons and helped me see through the bad in life, even when it felt like my world was crashing down on me. Lastly, thank you for always believing in me, even when I did not always believe in myself. I never could have done this without your support.
- To my family: Near or far, you have always been there to encourage and support me. You have always pushed me to follow my dreams, no matter how big or how far away. Momma, you are my hero and my inspiration. Thank you for being so strong for me and always showing me endless love. Papa bear, you are my strength. Because of you, I know I can do or be anyone I want. Thank you for reminding me that life does not have to be all work, but the fun is what is important too. Sarah, you are my motivation. You have created such a beautiful family. I strive to have that someday. In the meantime, I will be the best aunt I can be. Thank you for being the best big sister I could have ever asked for. Jagger, you are my sanity. Getting you at the start of grad school may not have been the smartest, but it was the best decision I could have ever made. Even on my worst days, coming how to a loving puppy was all I could ask for. Thank you for being there to accept my hugs, give me puppy kisses, and remind me that in the end, life will be just fine as long as I have my pooch by my side.

Always remember to believe in yourself and dream big.

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ABSTRACT

DIFFERENCES IN RUNNING MECHANICS BETWEEN OVERWEIGHT/OBESE AND HEALTHY WEIGHT CHILDREN

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Background/Purpose: Physical activity is commonly prescribed to reduce childhood obesity. However, due to differences in mechanics during low-impact activities, such as walking, obese children may be more prone to negative physical complications during high-impact activities, such as running. Therefore, this study analyzed the mechanical differences in running mechanics between healthy weight (HW) and overweight/obese (OV/OB) children. We hypothesized that when compared to HW children, OV/OB children would display higher vertical loading, greater joint moments and greater joint angular impulses during running. We also expect decreased sagittal plane range of motion and increased frontal plane range of motion of the hip, knee, and ankle joints in the OV/OB group during running. **Methods:** Ground reaction force (GRF) and joint kinematic data were collected for 42 children (25 HW, 17 OV/OB) while they ran across an implanted GRF platform at a given speed of 3.5 ± 5% m/s. Spatial-temporal and joint kinetic data (ankle, knee, & hip) were also determined. A one-way ANOVA was used to compare group differences for all variables of interest ($p<0.05$). Box plot analyses were used to identify and remove outliers. **Results:** Compared to HW children, OV/OB children displayed significantly greater: stance time, shorter step lengths, absolute GRF's, and relative GRF's, specifically, the peak vertical force, the vertical impulse, braking impulse, and propulsive impulse. In addition, OV/OB children experienced significantly greater knee adduction and hip abduction moments. **Conclusion:** Exercise progression for OV/OB children from low impact to high impact activities should be considered when prescribing exercise. This progression could allow the body to adapt to the increased physical demand over time and decrease the child's risk of pain or injury.

KEY WORDS:

Joint Kinematics, Joint Kinetics, Ground Reaction Forces, Physical Activity, Injury

LITERATURE REVIEW

This literature review looks to capture the findings on the topics of childhood obesity and biomechanics as it relates to the proposed study. Throughout this review, the reader will obtain a better understanding of the worldwide growth of obesity, weight management, the progression of obesity from childhood to adulthood, the consequences of obesity, and how obesity is assessed. In addition, an overview of the biomechanical considerations are presented. Biomechanical topics include mechanical development and its effect on the body in static and dynamic situations, joint angles and moments, ground reaction and joint reaction forces, associated risks, and methods to collect data for obese participants. This literature review intends to critically analyze the published information with regards to the proposed topic.

Childhood Obesity

From 1980 to 2010, obesity rates for children 6-11 years of age within the United States have increased by 11%.[1] Similar trends were reported for children 12-19 years of age recording a 13% increase throughout the same time frame.[1,2] Spain, the United Kingdom, France, and Greece have all reported increased childhood obesity rates over the last three decades.[3,4] According to the Organization for Economic Co-operation and Development (OECD), one in five children across the countries of Brazil, Mexico, and Canada are overweight or obese.[5] Similar to the United States, Greece and Italy's childhood obesity rates are nearly one in three children.[5] While the findings from Tambalis et al. suggest that childhood obesity levels have plateaued in recent years, the number of children with excess body weight from adipose tissue remains high.[1,6] Not only has obesity increased the number of individuals suffering from long term health consequences such as cardiovascular and metabolic diseases, obesity is also associated with an increased risk of physical consequences including skeletal mal-alignments and joint degenerative diseases.[7]

Understanding obesity and its main causes may help clinicians and health professionals to reduce childhood obesity rates worldwide.

Research suggests that increasing physical activity, decreasing sedentary time, and improving diet are among the leading methods in decreasing childhood obesity rates.[8-11] Children who participate in regular physical activity and receive proper nutrition are better suited to reach full growth and development.[11] However, a lack of physical activity and poor eating patterns makes children more susceptible to increases in body weight.[12] Sustaining excess body weight throughout childhood is associated with risks that can be detrimental to the child's future. Excess body weight may limit physical growth and increase their risk of injury and development of negative health outcomes such as metabolic syndrome.[13,14] Understanding the relationship between these primary factors will help researchers combat childhood obesity by developing preventative measures and treatments for our youth.[15,16] By limiting the negative effects of obesity, health professionals can help children to reach their full development and reduce the risk of both injury and negative health consequences.

To fully comprehend the impact of childhood obesity, researchers must evaluate weight gain and weight loss, the risks of becoming an obese adult, and obesity associated health consequences. Weight management, particularly weight loss is increasingly important as children accumulate excess body weight. As children sustain excess body weight, their likelihood of maintaining that weight into adulthood increases resulting in a greater risk of both physical and health complications.[17] By understanding these consequences, we can help to educate OV/OB individuals and promote healthier lifestyles. Without proper education children may continue to add on body weight throughout their lifetime which may reduce their overall quality of life.[18]

Weight Management

An increase in body mass adiposity can be explained by an increase in caloric consumption and/or a decrease in caloric expenditure.[19-21] Increases in caloric consumption have been related to increased portion sizes, increased snacking, and reduced consumption of food made from within the home.[19,22] Ford et al. found adjusted mean energy intake increases of 1,955 kcal/day from 1971-1975 to 2,195 kcal/day from 2009-2010.[21] As food consumption outside the home increases, individuals are consuming more calories per day with poorer food quality when compared to food consumption made from within the home. Reducing caloric intake may be one method to help OV/OB children decrease excess adipose tissue over time.

In addition to increased energy intake, decreased energy expenditure has been reported due to decreased physical activity participation.[19] According to the Center for Disease Control and Prevention (CDCP), children and adolescents should engage in 60 minutes or more of physical activity every day.[23] Recommended physical activities should include aerobic, muscle-strengthening, and bone-strengthening exercises with at least three days per week including vigorous intensity exercise. Aerobic exercise varies by intensity with a brisk walk being a moderate intensity and running a vigorous intensity.[23] Common muscle and bone strengthening activities such as push-ups, jumping jacks, and body-weight movements assist in muscle and bone growth that is essential throughout life.[23] Promotion of physical activity each day is essential for the development of strong bones. Regular participation in weight-bearing activities assists in building and maintaining bone and muscle which is highly important throughout the growing stages of childhood.[23] Approximately 90% of bone mass development occurs during adolescents.[24-26] Bailey et al, found a 9% and 17% increase in total body bone mineral density in active boys and girls, respectively, compared to their inactive peers.[24] Physically inactive children decrease their odds of developing their bone to optimal growth levels which may make them more susceptible to injuries during falls, collisions, and/or crashes.[27]

Unfortunately, many children do not meet physical activity guidelines.[28] Research collected using a self-report survey has shown that fewer than 50% of children reach the recommended amount of physical activity of at least five days per week for at least 60 minutes.[29] Other reports from the CDCP show the percentage not meeting guidelines closer to less than 30% across the United States. This shows that throughout a child’s day, children are engaging in less physical activity than ever before.[30] This decrease in physical activity has been suggested to be a result of less physical education and recess time, decreased participation in after school activities, and decreased physical activity at home.[30]

In addition to physical inactivity, the amount of sedentary time a child accrues daily may impact their overall energy expenditure. Developed countries such as the United States have reported increased levels of sedentary time.[31] Sedentary time refers to any activity characterized by an energy expenditure ≤ 1.5 metabolic equivalents, typically in a sitting or reclined position; excluding sleep.[32] Berkey et al. found a significant relationship between increases in Body Mass Index (BMI) and sedentary time, with sedentary time described as time spent watching television, playing video games, or time on the computer. [15,33] [34] Today, children in the United States have higher levels of sedentary time than previous generations making sedentary time a major concern.[10,31] Due to these increases, the American Academy of Pediatrics recommends that youth over two years of age spend no more than two hours each day with screens. Wethington et al, conducted a study using the 2007 National Survey of Children's Health data and found overall, 20.8% of 6-11 year olds and 26.1% of 12-17 year olds had excessive screen time (>2 hours per day).[10] In addition, for both age groups, children with a bedroom TV reported significantly higher screen time at 27.6% compared to children without a bedroom TV at 14.7%.[10] Maher et al, found that high screen time was associated more strongly with obesity than the individual's amount of moderate-to-vigorous physical activity.[31] The combination of increased BMI and sedentary time may result in less bone mineral density for obese children resulting in a greater risk of injury or joint degenerative diseases.[35] In addition to physical concerns, increased sedentary time has shown to produce negative long term health effects such as cardiovascular and metabolic risk factors.[33,36] Recent research indicates that sedentary time is considered as its own independent risk factor for cardiovascular disease, all-cause mortality, and physiological and psychological complications.[9,36]

While the primary reasoning for the increase in body mass in the United States remains undetermined, a combination of increased energy intake and decreased energy expenditure are key contributors.[12] Exercise prescription targeting OV/OB children is important since these children are already carrying excess adiposity. While in general, obese children have comparative upper extremity strength when compared with non-obese peers, Riddiford-Harland et al. found that during weight bearing activities, obese children's lower limb function was significantly hindered.[37] The impact regular physical activity participation has on children's vertical load rates and other gait mechanics remains unclear. While a child's body undergoes many physical changes throughout adolescence, participation in regular physical activity has been shown to increase bone density, which may influence the child's ability to adapt to increased loading during common physical activities when compared to a physically inactive child.[11,38] If OV/OB children experience increased load rates during high impact activities, such as running, they may be increasing their risk of injury and joint degenerative diseases. While the benefits of increased physical activity outweigh the risks of injury associated with physical activity participation, exercise prescriptions for OV/OB children must consider the mechanical implications of high impact exercise while promoting regular physical activity participation.[9] Physical activity for OV/OB children may need to be modified in order to reduce the potential for injuries associated with increased obesity. [27,39]. Additionally, understanding the implications infrequent participation in high-impact exercises may have for inactive children regardless of weight status is important. To reduce obesity rates, focus must be placed on improving dietary habits and increasing participation in physical activity. Providing OV/OB individuals with the knowledge to make healthy dietary and exercises choices is essential to the reduction of obesity around the world for individuals of all ages.[29,40]

Childhood Obesity into Adulthood

The positive association between childhood and adult obesity is not surprising given BMI increases are positively associated with increasing age.[4,7,17,40,41] Freedman et al. analyzed data from a cross-sectional (n=10,099) and longitudinal (n=2,392) study of children ranging from ages 5 to 17 years (mean age of 11.4 years). Of children with a BMI between the 95th and 98th percentile, classified as obese, 84% became obese adults.[7] All children with a BMI $\geq$ 99th percentile, classified as morbidly obese, became obese adults.[7] After age six, the probability of an obese child becoming an obese adult surpasses 50%, while non-obese children's risk is approximately 10%.[17] To prevent obese children from becoming obese adults, additional measures must be taken to promote healthy living at a young age.

Being an obese adult leads to negative health consequences including risk of cardiovascular and metabolic diseases.[14] At any age, obese and non-obese children are more likely to become obese adults if even one of their parents is obese.[17] Children born to obese parents are more likely to be obese themselves.[17] While an obese child has an increased risk of becoming an obese adult, health strategies including exercise and diet can reduce these risks, thus decreasing the prevalence of obesity among children.[17] By decreasing the number of obese children from becoming obese adults, health professionals can limit the chronic negative health consequences experienced by the individual, therefore improving the overall quality of life of children.[40]

In addition to negative health consequences, excess body weight sustained from childhood into adulthood may increase a child's risk of suffering from lower extremity injuries and joint degenerative diseases.[35,42,43] Lerner et al., found that during walking, obese children have increased vertical ground reaction forces on their lower extremities when compared to non-obese children.[44] Increased vertical ground reaction forces are associated with an increased risk of injury and joint degeneration.[45] Depending on the child's rate of development, their body may not be able to accommodate the excess mass and therefore may not be able to adapt to the increased forces.[35] Previous research displayed that as body mass increases, the surface area of adjoining bones does not increase proportionately.[35] Without proper adaption of the lower extremity skeletal structure, a child's risk of injury and joint degeneration may be increased.[46] Preventive measures need to be taken to reduce the increased ground reaction forces experienced by OV/OB children while decreasing the risk of becoming an obese adult.

Consequences of Childhood Obesity

In addition to injury and the potential risk of developing joint degenerative diseases, childhood obesity has been reported to lead to a number of acute and chronic negative health consequences. Evidence suggests that due to obesity, for the first time in over a century, life expectancies in the United States are anticipated to decrease.[11,47] Obese children are more prone to acute cardiovascular risks such as hypertension and hypercholesterolemia than non-obese children.[7,15,48,49] Data collected from children with a BMI $\geq 95^{th}$ percentile showed that 70% of obese children have a minimum of one risk factor for cardiovascular disease.[7,50] As expected, the percentage of obese children suffering from at least one cardiovascular disease risk factor increased as BMI increased toward the 99^{th} percentile.[7] National data indicates that children classified as OV/OB are approximately 10 times more likely to have at least two risk factors for metabolic syndrome than those classified as non-obese.[51] Developing strategies to reduce childhood obesity may lessen these risk factors while increasing life expectancy.

However, as the duration of time spent being obese increases, the risk of susceptibility to long term health issues increases.[27] Chronic effects of childhood obesity have been reported in association with heart disease, stroke, osteoarthritis, and certain cancers.[49,52] Specifically, vascular fatty streaks, raised lesions in the coronary arteries and aorta, increased left ventricular mass, and premature mortality are prevalent with obese individuals.[7,53] However, OV/OB children who meet dietary and physical activity guidelines decrease their risk of suffering from these negative health related issues.[54]

In addition to a child’s physical health, obesity impacts children in many other aspects of life. Childhood obesity has been associated with symptoms of depression and reduced self-esteem.[9,55] Research indicates that severity of obesity is positively and negatively correlated to the child’s level of depression and quality of life respectively.[55] Regardless of a child’s mental and weight status, children who meet physical activity guidelines set by the CDCP display improved academic performance.[54,56] Increased physical activity levels have also been shown to improve children's overall behavior in and out of the classroom.[56] A strong positive association was found between physical activity and improvements on measures of anxiety and depression symptoms, dependent on mode of exercise.[38,57] Reducing obesity during childhood may help children to be more confident and successful throughout their lifetime.

As childhood obesity rates remain at an all-time high, strategies must be taken to treat, inform, and prevent further occurrence of this epidemic. Arguably the most important strategy for decreasing obesity rates is promoting physical activity. Although physical activity is an important method used to reduce obesity, considerations must be given to the potential negative consequences weight bearing activities, such as walking, running, and jumping may be having on obese children.[2,44] If obese children are experiencing increased joint loading during weight bearing activities, health professionals may need to reevaluate how exercise is prescribed. Proper reevaluation would include keeping children active through a combination of weight bearing and non-weight bearing physical activities. Promotion of proper exercise prescription for obese children is an important step to decreasing obesity rates while maintaining joint health.

Assessment of Obesity

A variety of options are available to determine a child's body fat composition. Commonly used methods include the dual-energy x-ray absorptiometry (DEXA), hydrostatic weighing, bioelectrical impedance, BMI calculations, and skinfolds.[58] While DEXA is considered the gold standard for determining body fat percentage, a commonly used measure developed by the CDCP incorporates the child's date of birth, gender, height, and weight to determine BMI for children specific to their demographics.[59] This BMI is analyzed on a growth chart (Figure 1 – Chart for boys) to determine whether the child is classified as underweight (< 5th percentile), healthy (≥ 5th and < 85th percentile), overweight (≥ 85th and < 95th percentile), or obese (≥ 95th percentile).[7,27,39,60] BMI percentile has been established as an accepted method for determining body composition for ages 2 through 19 years with validation across many national and international studies.[7,59,61-65] Using BMI percentile is very important for the 2-19 age group. Throughout this time frame, a child's body can vary greatly, depending on their maturation level, thus accounting for age, height, weight and sex can provide a more accurate depiction than using an absolute BMI would. The BMI percentile calculator also serves as an efficient, reliable, and cost-effective measurement tool for evaluating body composition in children and provides researchers with the necessary information to correctly categorize children's BMI. CDCP's BMI-for-children calculations are a nationally accepted method that are easily operated and provides researchers the necessary information to properly group the participants by weight status.

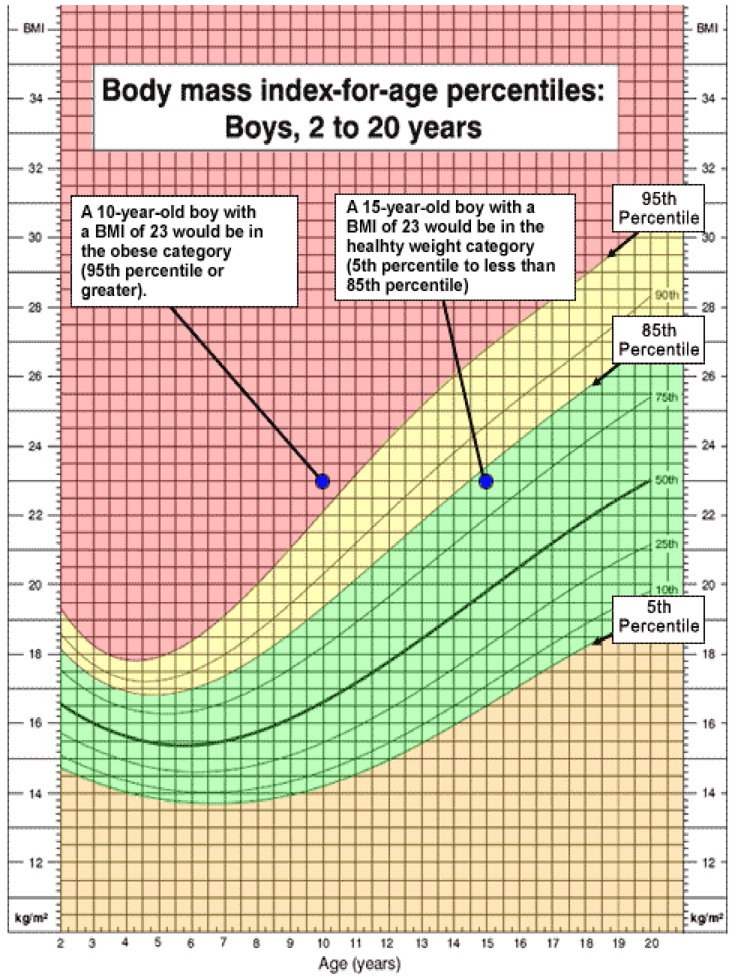


Figure 1: BMI Percentile growth chart for boys[1]

Biomechanical Considerations

While biomechanical analysis of human motion has allowed researchers to increase their overall knowledge of human movement, research is still lacking regarding the impact obesity has on the biomechanics of human movement. In 2012, more than one third of Americans were classified as OV/OB.[66] This trend has led to many concerns regarding the impact of obesity on the body during activities of daily living and common physical activities. Some of these concerns include increased frequency of lower extremity pain, injury, and joint degenerative diseases experienced by obese individuals.[27,67]

Developmentally, early childhood (4 to 6 years) to early adolescence (12 years) may be considered one of the most important developmental stages in life.[68] Throughout early childhood and adolescence, a child's ability to develop fundamental motor skills is at an optimal level.[69] An important aspect in the progression of these motor skills includes physical activity. Participation in physical activity helps teach children how to control their movements and how to interact with their surroundings.[70] In addition, participation in physical activities during childhood aids in increasing bone density, potentially decreasing their risk of bone injury.[71] Bonjour et al, found that a major determinant of risk for fractures was reduced bone accrual during childhood and adolescents.[72] If an obese child is unable to adequately increase bone density, the lower extremity bone structure may experience increased forces due to excess adiposity.[46] The bones and joint articulations of obese children have been reported to not grow proportionate to the amount of weight gained.[2,73] The increased weight without a proportionate increase in joint surface area will increase the joint reaction forces occurring during physical activity. Failure to compensate for these increased forces may result in an increased risk of pain, injury, and joint complications.[74]

The mechanical implications obesity has on the skeletal framework of a child's body is cause for major concern. Commonly experienced complications include increased risk of lower extremity mal-alignments, slipped capital femoral epiphysis, and increased joint loading during walking and landing tasks.[2,35,75,76] Each of these complications may impact a child's injury risk, perception of physical activity, and overall willingness and capability to be physically active.

Associated Risks

Obesity causes many negative physiological and mechanical implications on the body. Some of these negative effects include increased risk of cardiovascular and metabolic diseases and development or progression of joint degenerative diseases. Not only is obesity an issue, but the severity of the obesity also becomes a factor. As a child's BMI increases the risk of experiencing lower extremity pain or injury increases.[27] In addition, as severity of obesity increased, the risk of experiencing musculoskeletal pain increases.[77] Of 135 children, 61% reported musculoskeletal pain with the highest reported areas being the back (39%), the feet (26%), and the knees (24%).[77] Children who are moderately obese are 25% more likely, and severely obese are 35% more likely, to experience a lower extremity injury than non-obese children.[27] Similarly, Kessler and colleagues found that overweight, moderately obese, and extremely obese children were all at an increased risk of fractures to the foot, ankle, and knee compared to non-obese children at all ages.[78] Of these children, all had an increased odds ratio of foot fractures of 1.14, 1.23, and 1.42, respectively. In addition, at the ankle, knee, and leg their odds ratio was 1.27, 1.28 and 1.51 respectively. These findings suggest a relationship between excess adiposity during childhood and risk of musculoskeletal injury.

Osteoarthritis, a degenerative disease of the movable joints, is a major risk factor associated with obesity; particularly common in the knee and hip joints.[74] Felson et al, found the prevalence of osteoarthritis is dramatically increased in the obese population compared to the non-obese population for both genders.[74] Similarly, Cooper et al, found an increase in BMI is related to an increased likelihood of suffering from osteoarthritis.[79] Women were at a greater risk than men at each given BMI for developing osteoarthritis.[74] Individuals with a BMI > 28 (kg/m^2) were 1.7 times more likely to suffer from hip osteoarthritis compared to those with a BMI < 24.5 (kg/m^2).[79] While the odds of an obese individual developing osteoarthritis is significantly higher than those who are non-obese, their additional risk of injury may put them at an even greater odds since prior injury also increases the risk.[79]

The best proven method for reducing the odds of suffering from these risks is decreasing excess body weight.[80] Participation in physical activity is the best method of losing this excess weight, however exercise prescriptions must consider the loads placed on the body during different types of exercise. It may be necessary to develop a progression from low- to high-impact exercises to reduce the potential effects of increased vertical loading displayed during some activities.

Static and Dynamic Situations

Static Situations

Obesity throughout adolescence has been shown to have adverse effects on bone maturation and alignment.[35,81] Overweight children report more orthopedic complaints including musculoskeletal discomfort and lower-limb mal-alignment when compared to HW.[35,42] Mal-alignments experienced by OV/OB children appear to increase joint instability which may result in further complications to an already vulnerable area.[82]

Commonly diagnosed mal-alignments include genu varum (bowing of the legs) and genu valgum (knocked-knees). A study conducted by Taylor et al, used DEXA scans to examine lower extremity alignments in children.[35] This study found that metaphyseal-diaphyseal and anatomic tibofemoral angle measurements, both of which are used to represent degrees of varus alignment, showed greater mal-alignment for overweight children compared with HW children.[35] Both genu varum and genu valgum result in uneven loading of the joints which may increase the risk of joint degeneration.[35,83] As can be seen in Figure 2, excessive genu valgum or genu varum increases loads on the medial and lateral femoral articulations respectively. Both genu valgum and genu varum mal-alignments have been reported to increase

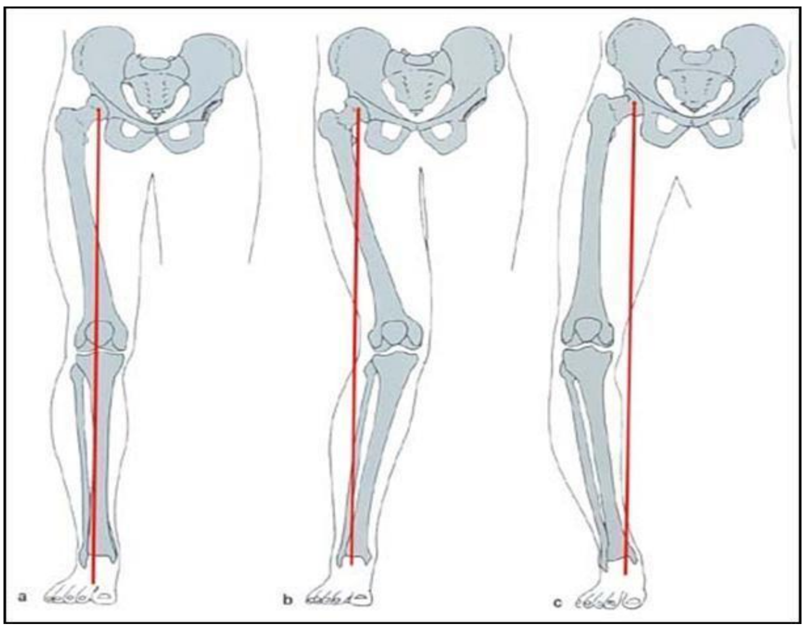


Figure 2: (a) normal alignment, (b) genu varum, (c) genu valgum

the risk of developing knee osteoarthritis.[83,84] Depending on the severity of the child's obesity and of their mal-alignment, immediate steps may need to be taken to correct the mal-alignment. Pirpiris et al. found a clear association between increased BMI and children requiring surgery for the treatment of Blount's disease, a disease causing the lower leg to angle iHWard.[85] Failure to correct a mal-alignment may result in further damage to the lower extremity joints including a commonly associated effect, osteoarthritis.[42,82,86-88]

The relationship between adult obesity, mal-alignments and the progression of osteoarthritis has been well established.[43] Schouten et al. found a five-fold increase in the progression of osteoarthritis for adult patients who suffered from genu varum or genu valgum throughout childhood.[89] Similarly, Messier et al. showed a fourfold increase in knee joint compressive forces for every pound increase in body weight.[84,90] Not only does obesity increase the likelihood of total joint replacement surgery among younger adults, but it has a clear impact on the structural development, primarily at the knee, which may hinder the functionality of the hip.[91] A common hip injury experienced by obese children is slipped capital femoral epiphyses (SCFE) as seen in Figure 3. SCFE occurs when the proximal femoral epiphysis separates from the metaphysis, in a non-traumatic occurrence.[92] The inability for the skeletal system to sufficiently

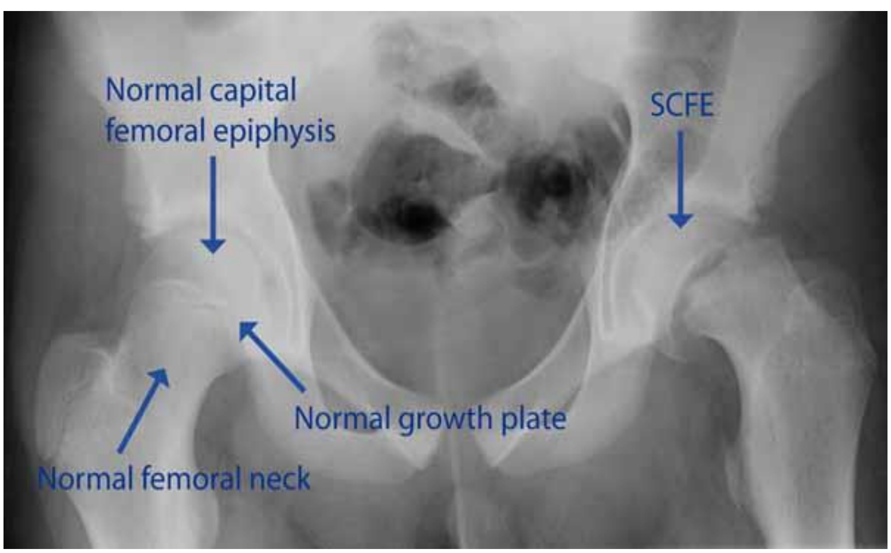


Figure 3: Normal (Left) versus Slipped Capital Femoral Epiphysis (Right)

adapt to excessive body weight is reported to being the leading causes of SCFE.[75,87,93] Manoff et al., found that of 160 children who had suffered from SCFE, 81.1% of these individuals had a BMI above the 95th percentile.[94] Furthermore, there appears to be an association between BMI and the development of bilateral versus unilateral SCFE, with the mean BMI of patients suffering from bilateral SCFE being significantly greater than that of patients with unilateral SCFE.[93] While the main cause of SCFE is unknown, many researchers believe that mal-alignments commonly found in OV/OB children combined with increased loading during walking and other movements predispose OV/OB children to the development of SCFE.[92]

For OV/OB children suffering from a mal-alignment, increased forces on the knee joint may result in force increases at the hip joint. Force increases at both the knee and hip joint may result in a higher sensitivity to injury, especially during high-impact activities.[94] While reducing a child's weight can help lower an OV/OB child's risk of mal-alignment, if SCFE occurs, surgery is needed to correct it.[94] Undergoing surgery can result in extended periods of non-weight bearing activity, further hindering bone growth and development.[95] The negative effect of poor bone mineral density during childhood is likely to have lasting effects that may have negative consequences leading up to and throughout adulthood.[24]

To reduce the negative implications of obesity related mal-alignments, health professionals need to consider methods to lessen or eliminate a child's risk of suffering from a mal-alignment. First, regular participation in physical activity should be considered to reduce the child's weight.

Weight reduction by an OV/OB child may alleviate stress experienced at the lower extremity joints. While participation in physical activity is important for weight reduction, researchers must prescribe activities that will protect OV/OB children from further harm. Exercise prescription should consider a combination of weight bearing activities and non-weight bearing activities, such as swimming, to reduce the child's weight. Weight reduction is associated with a decreased risk of mal-alignments and the negative consequences associated with mal-alignments.[43] In addition, preventative measures including brace treatments or surgery could be considered to limit long term effects. If left untreated a mal-alignment may worsen and could result in increased pain levels, further disruption to normal gait patterns, and/or deterioration of bone and tissue of the lower extremities which may limit the child's ability to participate in activities of daily living.[25]

Dynamic Situations

The negative implications of mal-alignments displayed by OV/OB children in static situations may be exacerbated during dynamic situations. Throughout adolescence, children participate in walking, running, and many other weight bearing physical activities in various, infrequent amounts every day.[96] Weight-bearing activities such as walking, running, and jumping help in the development of muscle and bone. These activities assist in the development of bone mineral density which promotes the ability to perform proper movement techniques.[97] However, when compared to non-obese children, the physical demands of performing weight-bearing activities by obese children is greater due to their increased mass.[98] When an obese child suffering from a mal-alignment participates in physical activities, there may be substantial loading unevenly distributed at the knee.[99] Uneven loading in addition to increased force due to the excess mass may significantly increase the child's risk of pain, injury, and joint degeneration even in an everyday activity, such as walking.[43]

For most individuals, walking is an essential part of human movement. Walking can improve health related risks by increasing physical activity and decreasing sedentary time. However, the gait of an obese individual appears to differ from that of a non-obese individual. McGraw et al. found that compared to non-obese prepubertal boys, obese prepubertal boys had significantly greater dual stance and mediolateral sway areas during gait.[100] Increased time in dual stance may suggest decreased stability by obese individuals, while increased sway areas may be due to excess adiposity located on the upper leg.[100] Obese children also appear to walk more rigidly, with less knee joint movement, and have a flatter food during ground contact.[76,101,102]

Decreased range of motion and increased rigidity during walking is associated with the force-time relationship.[103] Since the child has limited range of motion, there is limited time for the force to be applied resulting in increased vertical forces.[103] When obese children walk with a reduced performance, they may be more susceptible to increased pain, injury, and joint degeneration throughout life.[104] Furthermore, the gait of obese adults during walking also appears to be hindered.[105] When compared to non-obese adults, obese adults land with a stiffer leg during self-selected and given walking speeds.[105] Walking with a stiff gait increases the amount of force placed onto the lower extremities, which can compromise the surrounding bone and tissue.[106] If the bone and tissue surrounding the lower extremity joints is compromised, the person's risk of pain, injury, or joint degeneration may be further heightened.

Not only do obese adults display altered walking mechanics, but they are doing so less efficiently. LaRouche et al. found that obese adults display a 62% greater absolute and 20% greater relative cost of walking when compared to non-obese adults completing the same task.[107] The extraneous work performed may cause obese individuals to fatigue faster than normal which may worsen their mechanics creating a greater risk of injury.[98] The negative implications of obesity during walking are concerning given that when compared to other physical activities, such as running and jumping, walking is a relatively low-impact activity.

Regardless of a child's mass, as physical activity progresses from low-impact, such as walking, to high-impact, such as jumping, the body will experience greater forces to the body during impact.[2,44] Furthermore, when body mass is accounted for, the total overall impact is even greater. While jumping has been shown to have many positive effects such as significantly improving bone density at the hip and lumbar spine in prepubescent children, obese children appear to land differently than non-obese children.[108] During landing, McMillian et al. found that obese boys exhibited significant sagittal and frontal plane differences compared to non-obese boys.[2] These differences included peak hip adduction moment, timing of peak dorsiflexion and knee flexion angles, and timing of peak knee extension and abduction moments which may increase their risk for lower extremity injuries when participating in landing activities.[2] McKay et al. found that when comparing a drop jump, counter movement jump, and jumping jack, the drop jump and counter movement jump performed by healthy children, resulted in 1.5 times more body weights of force compared to a jumping jack performed by these same children.[109] When compared to obese children, HW children experience less force during low- and high-impact activities.[2] Therefore, it is presumed that if McKay et al.'s study were replicated comparing obese children, we could anticipate even greater force differences between the different movements.[2] Thus McKay et al.'s findings suggests that if prescribing jumping exercises to obese children, the best type of jump to incorporate is the jumping jack as it allows the child to obtain the benefits of muscle and bone growth while reducing the force, thus reducing risk of developing pain or sustaining an injury.[96]

While the mechanical differences between obese and non-obese children during walking and jumping have been reported, there is limited information regarding the impacts of childhood obesity on running mechanics. Running is a common, vigorous intensity physical activity participated in by several individuals across the world. While running may be great physiologically to reduce obesity, there are many mechanical concerns regarding the participation of running by obese individuals. Increased forces experienced by obese individuals during walking will likely be further increased during running tasks.[44,76] In fact, in healthy individual's vertical loading rates experienced during walking increased from approximately 1.2 body weights of force to 2.5 body weights when running.[110] Furthermore, excessive vertical loading during running is highly associated with several different running injuries including, stress fracture, iliotibial band syndrome, plantar fasciitis, patella femoral pain syndrome and several others.[111] In order to determine if obese children are at an elevated risk for increased joint loading during running a thorough investigation of the running mechanics of obese individuals is needed.

Joint Angles and Moments

To understand why OV/OB and HW individuals perform dynamic activities differently, consideration must be given to the lower extremity joint angles and moments. Joint angles provide researchers with an insight into joint motions occurring during dynamic activities. During gait, researchers are often interested in the lower extremity joint angles and moments in the sagittal and frontal plane across stance. An examination of the joint mechanics during the stance phase of gait helps researchers understand if the movement is occurring correctly or incorrectly, allowing researchers to pinpoint problem areas. While running mechanics for obese children have yet to be analyzed, differences between OV/OB and HW children displayed during walking have provided health professionals insight into some functional limitations and provide a theoretical framework that can be used to make hypotheses about running mechanics.

Analysis of OV/OB individuals during walking indicates that OV/OB children display different sagittal movement patterns than HW children. Researchers primarily observe decreased hip and knee flexion during the stance phase of gait.[112] Decreased hip and knee flexion during gait is typically reported to be due to muscle weakness and/or injury of the hip.[113] When observing the hip during gait, obese adolescents display less hip flexion and significantly lower hip extension moments than the HW adolescents.[114] The reasons for these differences are likely due to t the excess mass of OV/OB children without the accompanying musculature needed to compensate.[115] If the musculature is unable to compensate OV/OB children may not be able to reach the optimal amount of flexion during gait, or their muscles may fatigue more quickly resulting in decreased joint flexion.[116] Furthermore, increased hip and knee flexion during stance is associated with eccentric loading of the knee and hip extensors which would require greater muscle force and a higher energy expenditure not preferred by OV/OB children.[116] Another reason obese children may land with decreased knee flexion may be due to the excess amount of adipose tissue surrounding the lower extremity joints.[44] Excess adiposity may be limiting the child’s range of motion thus hindering their ability to achieve a greater degree of hip and/or knee flexion during the stance phase of gait.[44] It is possible that the muscle weakness and/or limited range of motion causing decreased lower extremity flexion during stance, likely results in increased vertical loading, thus leading to pain, injury, or joint degeneration.[77] It stands to reason that these characteristics will be exacerbated as OV/OB go from walking to a running movement.

Frontal plane hip kinematics have been inconsistent. Some researchers have reported greater hip abduction angles during walking, which may be a result of increased leg circumduction or increased pelvic tilt due to hip abductor weakness. However, others report no differences between obese and non-obese individuals.[101] If hip abduction angles are increased during walking, the obese individual may be trying to compensate for increased adiposity surrounding the lower extremities. To compensate, obese individuals may adjust their gait to reduce knee joint loads. This gait adjustment may result in excess forces being unevenly distributed to the bone and tissues surrounding the lower extremity joints. Excessive force unevenly distributed could increase the risk of pain, injury, or joint degeneration of the hip for obese children and adults.[25,117]

Obesity's effect on joint kinematics appears to be greatest at the knee. In the sagittal plane, obese children have lower peak knee flexion angles during initial foot strike and during the late stance phase of walking compared to non-obese children.[101] These findings are consistent with findings from Ko et al., who reported decreased flexion throughout stance by obese adults when comparing HW adults.[118] In addition to decreased knee flexion, obese children experience lower knee flexion moments at the knee during foot strike and late stance which may be a method of compensation for potential weakness of the knee extensors or limited joint range of motion.[101,119] Muscle weakness and range of motion limitations may cause a disruption to normal gait. This disruption may result in an increased risk of knee instability which could result in a greater risk of pain or injury. If obese children are unable to produce enough knee flexion during stance they may increase the amount of loading placed onto the knee joint which is associated with many overuse running injuries such as, patellofemoral pain syndrome, tibial stress fractures, and plantar fasciitis.[76,120]

Obese children also display significant differences in frontal plane kinematics at the knee. Obese children report greater knee abduction during walking. These findings are not surprising due to their higher susceptibility of mal-alignments.[101] In addition, obese children display higher knee adduction and abduction moments during walking compared to HW children.[101] Atypical gait patterns at the knee may be putting unevenly distributed, excess stress on the joint structures. As seen with the mal-alignments genu varum and genu valgum, uneven loads are distributed to one side of the femoral articulations. Repeated stress to these unilateral surface areas is linked to further knee damage.[121]

A full understanding of what is occurring at the knee would be incomplete without having knowledge of what is occurring at the ankle. Research examining the ankle joint angles and moments of obese participants appear to be inconsistent. Gunther et al. report decreased plantarflexion angles, greater dorsiflexion angles, greater plantarflexion motion, and higher ankle moments by obese individuals when compared to non-obese.[122] Browning et al. reported no differences in ankle angles, but did find that obese individuals walked with lower muscle moments at the ankle.[123] Muscle weakness around the ankle joint may be attributed to the gait variations between obese and non-obese individuals. Browning et al. explains that lower plantarflexion moments exhibited by obese individuals during the stance phase of walking may be due to a decreased push-off.[123] The variation in findings may be due to differences in age of participants or speed of the tasks since Browning's participants were children performing tasks at a walking speed while Gunther's participants were adults, performing tasks at a running speed.

Obese children appear to adjust their gait to accommodate for their increases in weight and/or lack of strength to eccentrically load, thus researchers must still consider the repercussions of these accommodations. During stance, if an obese child lands with decreased hip, knee, and ankle-dorsiflexion, they are landing with increased leg stiffness. Landing with increased stiffness does not allow time for the lower extremity joints to absorb the shock being placed onto those joint. Consequentially, the lack of shock absorption by the lower extremity joints results in a greater amount of force. Increased force onto the lower extremity joints could lead to pain, injury, and joint degeneration.

A connection can be made between the lower extremity joint kinematics and an obese child's risk of mal-alignment. If a child is adjusting their gait due to excess adiposity, there can be repeated stressors placed onto the lower extremity joints, leading to a mal-alignment.[121] However, more importantly is the method of weight reduction. If health professionals want to reduce an OV/OB child's weight, they must also consider which activities can be performed without having unintended negative consequences such as excessive joint loading. Correction of gait kinematics may help OV/OB individuals to properly perform everyday tasks, such as walking while limiting harm to their body.[76] Since walking is considered a relatively low-impact exercise, we can assume that a high-impact activity, such as running, would cause the findings here to be far more pronounced.

Ground and Joint Reaction Forces

Mechanical loading during childhood plays a critical role in normal skeletal growth and development. However, decreased physical activity time and increased sedentary time may impact a child's ability to reach full development while increasing their risk of developing obesity. While Wolff's Law states that bone will adapt to the loads under which they are placed, it does not appear that the body of an obese child is able to adjust accordingly. This lack of adjustment causes an increased amount of force to be placed onto a relatively smaller surface area resulting in a greater risk of pain or injury. One method to reduce the amount of force placed onto the surface area is by decreasing leg stiffness. Leg stiffness is described as the mechanical characteristics of the spring-mass system, so when stiffness is increased the result is a greater force being placed onto the lower extremities.[124] In addition, leg stiffness is associated with the quantity of muscle activity about each joint.[124] By reducing leg stiffness, an OV/OB child may reduce the loads placed onto their lower extremities which can reduce their risk of injury or joint degeneration.

Another kinetic factor to consider effecting everyday activities is the influence of ground reaction forces, primarily the vertical force. As an individual increases in mass, it is expected that their vertical force will increase. During walking, obese children have been found to display increased vertical loading including vertical impact peak and vertical load rates when compared to non-obese children.[2,73] Both obese children and obese adults display similar increases to vertical loading when walking at a preferred and maximum walking speeds.[118] Increased vertical load rates have been associated with concomitant increases to joint loading at both the knee and hip joints.[122] In addition, increased vertical load rates have been linked to several overuse running injuries such as, plantar fasciitis and tibial stress syndrome, and to an increased risk for joint degenerative diseases including the risk and progression osteoarthritis.[101,125]

In addition to ground reaction forces, joint reaction forces are found using the net inertial moments and net muscle moments for the two proximal segments surrounding a joint. According to Newton's third law, for every action there is always an opposite and equal reaction. Schulz et al, found that overweight children displayed greater peak joint moments at the hip, knee, and ankle.[101] Specifically, the overweight children had significantly greater hip (flexor, extensor, abductor, and external rotator), knee (flexor, extensor, abductor, adductor, internal rotator) and ankle (plantarflexor, inverter, external and internal rotators) moments compared to HW children during walking.[101,121] These findings have been consistent in both self-selected and given walking speeds.[73,101] However, when normalized to body weight, many significant differences for peak joint moments are eliminated which emphasizes the impact of excess mass on absolute joint force during walking.[101] Devita and Hortobagyi,'03 found that when scaled for body weight, knee joint torque was significantly lower (46%), but ankle torque was significantly higher (89%) in the obese group compared with the non-obese group during walking at a given speed. This may be explained by an compensatory response by lower extremity joints when one joint has increased localized force on it.[126] Changes seen by obese children give researchers reason to believe that BMI increases raise the risk of suffering from pain in the lower extremities[77]. This increased force and/or loading on obese children's joints may leave them at a higher risk of lower extremity injuries and joint degeneration[27].

Both ground reaction force and joint reaction force data have been fairly consistent when comparing obese and non-obese participants, however joint power data has been conflicting. DeVita et al, found no differences in joint power between obese and non-obese adults at a given walking speed.[127] Interestingly, at self-selected walking speeds obese adults displayed less knee joint power.[127] MeaHWhile, Shultz et al, found significant differences between obese and non-obese children during walking for all power phases in the sagittal plane, hip and knee power weight acceptance and hip power at propulsion in the frontal plane, and knee power during mid-stance in the transverse plane.[101] Larger joint powers in obese children would increase difficulty in performing activities of daily living and may decrease willingness to exercise.[101] If an OV/OB child is producing greater force during running, they are at risk of experiencing a mal-alignment and atypical gait which could increase the child's risk of pain, injury, and/or joint degeneration. Further research must be collected to determine the true impacts of obesity on lower extremity joint power.

Collecting movement data of obese participants

Among the most important decisions in developing the methodology is determining which marker set to use to best capture the motion of obese individuals. Due to the large amount of subcutaneous adipose tissue on obese individuals, some marker set options could provide inaccurate results due to increased movement artifact. Lerner et al, compared the Helen Hayes marker set to an obesity-specific marker set as seen in Figure 4, which incorporated additional lower extremity markers including: medial femoral epicondyle, medial malleoli, and metatarsal 1 and 5 markers, as well as, sacral, thigh, and shank cluster markers. In addition, a spring-loaded digitized pointer was used to digitally mark the anterior superior iliac spines and iliac crests. Analysis of the obesity-specific marker set demonstrated the ability to replicate results from the modified Helen Hayes when no statistical differences were found for non-obese participants between the two marker sets.[128] However, when analyzing obese participants, the obesity-specific marker set resulted in significantly different peak hip flexion during stance and pelvic tilt angles when compared to the Helen Hayes marker set.[128] These significant differences may be attributed to the use of the sacral cluster in unison with virtual markers to digitally model the movement of the pelvis. The obesity-specific model can be compared versus the use of standard markers that are subjected to increased artifact due to the high adiposity surrounding the pelvic region. While standard markers have been accepted as a valid method of tracking movement for non-obese individuals, researchers must consider the impact excess adiposity causes when assessing the movement of OV/OB individuals.

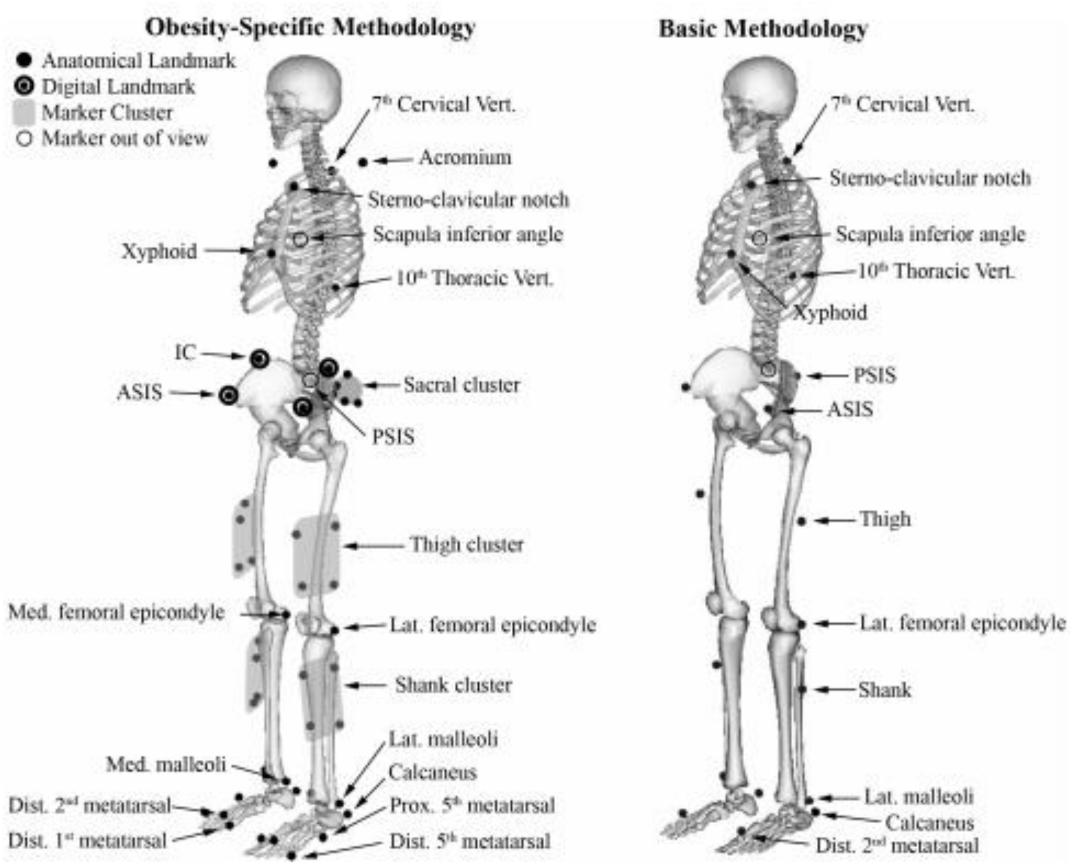


Figure 4: Modified Helen Hayes versus Obesity-Specific Marker Set[128]

Summary

Childhood obesity has rapidly progressed worldwide in the last three decades. [8,129,1,3,4,66] Physical activity is a key target for preventing and treating childhood obesity. Guidelines provided by the CDCP recommend children engage in 60 minutes or more of physical activity every day including aerobic, muscle-strengthening, and bone-strengthening with at least three days per week of vigorous intensity aerobic exercise.[23] However, commonly prescribed aerobic activities such as running and jumping are considered high-impact activities. Pilot data has shown that during running, obese children display increased leg stiffness, increased vertical loading, and decreased lower extremity joint flexion. Activities of high-impact may cause harm to obese children by increasing the forces placed onto the lower extremities resulting in a greater risk of injuries and joint degeneration.[60] In addition, obese adults have been shown to display less flexion of the lower extremities and greater vertical forces during both walking and running tasks. While it is likely that differences in running mechanics between OV/OB children and non OV/OB children will result in similar findings to those found for the walking movement, research conducted analyzing the obese children's running mechanics is scarce. To our knowledge no research has been completed analyzing the kinetic and kinematic variables of running between obese and non-obese children.

In order to decrease childhood obesity rates we must get children involved in regular physical activity. However, further research must be completed to fully understand the implications high-impact exercises such as running and jumping may have on obese children's bodies. Understanding these variations may allow health professionals to individualize exercise prescription for obese children which may decrease risk of injury, joint degeneration, and other lower extremities complications. Improving the knowledge on obese children's mechanics may provide parents, educators, and researchers the proper insight to improve obese children's quality of life now and into the future.

INTRODUCTION

Within the United States, approximately one in three children is currently classified as overweight or obese (OV/OB).[19,129] To combat against obesity, the Center for Disease Control and Prevention (CDCP) has suggested that children participate in a minimum of 60 minutes of aerobic exercise per day.[23] Regular participation in physical activity throughout a childhood is not only important to reduce obesity, but also enables bone and muscle growth.[130] While the physiological benefits of increasing physical activity have shown positive results, evidence is lacking regarding the mechanical loads placed on the body of an OV/OB child during many physical activities recommended by the CDCP.[131]

During physical development children undergo a variety of changes including rapid skeletal growth and muscle maturation.[132] During this phase of rapid change, obese children display different movement mechanics than non-obese children. During walking, these differences include slower self-selected walking speeds and greater time spent in double support.[76,121] In addition, obese children walk with a more rigid posture, displaying less flexion at the hip and knee.[76] Decreases in range of motion at the hip and knee joints during gait are often associated with increased vertical loading and leg stiffness. Stevens et al., reported increased vertical load rates for obese children during walking when compared to non-obese children.[83] In addition, Hills and colleagues reported similar findings showing that obese children are exposed to considerably high loads with joint reaction forces of approximately three to five times their body weight during walking.[103,119] Increased vertical loading displayed by obese children may explain the significant association between childhood obesity and lower extremity injuries, including the common injury, slipped capital femoral epiphysis.[92]

Although mechanical loading is necessary for proper bone growth and muscle development in children, excessive loading may lead to joint injuries or joint degenerative diseases. Research indicates that as body mass excessively increases, joint surface area does not increase proportionally.[35] Subsequently, the increased weight is distributed over a relatively smaller surface area resulting in greater joint reaction forces to the lower extremity joints.[101] The additional joint stress has been suggested to lead to musculoskeletal mal-alignments in obese children including slipped capital femoral epiphysis and Blount's disease or tibia vara.[35,92] These mal-alignments combined with increased loading during dynamic activities may lead to joint degenerative diseases, such as osteoarthritis, later in life. Both unilateral and bilateral knee osteoarthritis has already been linked to excessive joint loading and mal-alignments in obese adults.[84,106]

While obesity has been linked to increased vertical loading during low impact activities, higher impact activities, such as running, may result in even greater loads acting on the lower extremity joints. Although running mechanics have yet to be observed in obese children, greater loading displayed by obese adults has been linked to the development of joint degenerative diseases, such as osteoarthritis.[67] Additionally, increased vertical loading experienced by healthy runners (26 ± 2 years of age) has been linked to tibial stress syndrome, plantar fasciitis and has also been suggested to lead to osteoarthritis.[133] Considering the similarities in mechanics between obese adults and obese children during walking, and the higher impacts associated with running compared to walking, it is likely that obese children will also display increased vertical loading during running. However, there is currently no known research that examines the running mechanics of OV/OB children.

Due to the increased injury risk displayed by adult runners experiencing increased vertical loading and the greater prevalence of knee osteoarthritis in obese adults, it is likely that obese children will experience increased loading during running. While CDCP guidelines recommend that children participate in a minimum of 60 minutes of aerobic exercise every day, these guidelines also suggest participation in vigorous-intensity aerobic exercises, such as running, a minimum of three days per week. It is undetermined if OV/OB children can safely participate in high impact activities without increasing their risk of injury or joint degeneration.[23] Therefore, the purpose of this study was to determine the mechanical differences between OV/OB and HW children during running. Based on obese children and adult's commonalities in walking mechanics, we hypothesized that OV/OB children will display higher vertical loading during running compared to HW children. Furthermore, we expected joint moments and joint angular impulses to be higher for the OV/OB children compared to HW children. Lastly, we expected decreased sagittal plane range of motion and increased frontal plane range of motion of the hip, knee, and ankle joints in the OV/OB group during running.

Increasing physical activity among children is an essential component of reducing childhood obesity rates.[1] Equally important, is understanding the potential harmful risks of increased vertical loading during high impact activities. By examining the running mechanics of OV/OB children, greater insight can be provided on the potential risks that running may have for these children. Furthermore, teachers, parents and other clinicians would be better equipped in prescribing appropriate physical activities for OV/OB children that would still meet the CDCP guidelines for physical activity for children.

METHODS

Participants

A Physical Activity Readiness Questionnaire, Injury History Questionnaire, and informed assent and consent waivers as approved by the Institutional Human Subjects Review Board were completed by the participant and participant's guardian prior to participation. All participants had to be deemed healthy and free of injury during the previous three months to be eligible. An *a priori* power analysis using pilot data was used to determine the sample size needed to achieve statistical significance. Based on the power analysis, 42 participants were needed to adequately power this study (effect size =0.80, α =0.05, β = 0.20). Forty-two children between 8-12 years of age were recruited to participate in this study. Participants included 17 OV/OB participants (BMI $\geq 85^{th}$ percentile) and 25 HW participants (BMI < 85^{th} percentile). Participant demographics are displayed in Table 1.

Instrumentation

Twenty-seven reflective markers and two cluster markers were used to identify anatomical landmarks of the lower extremities using a modified Helen Hayes marker set. Inclusion of iliac crest and greater trochanter markers, as well as, thigh and shank clusters were used to limit artifact for the OV/OB children. Three-dimensional marker coordinates were collected using an eight camera (Oqus-3) Qualisys motion capture system (Qualisys, Gothenburg, Sweden) with a sampling frequency of 200 Hz to determine kinematic data. Ground reaction forces (1000Hz) were collected using an AMTI force platform (AMTI, Newton, MA) embedded in a 15 m ruHWay. Kinematic and kinetic data were synchronized using Qualisys Track Manager (Qualisys, Gothenburg, Sweden).

Procedures

Participants underwent a single two hour testing session at a university biomechanics laboratory. Following assent and consent, the participant's name, date of birth, and sex was recorded. Height (m) and weight (lbs) were measured using a stadiometer and AMTI force plate

(AMTI, Newton, MA) respectively. Both height and weight were used in calculating Body Mass Index (BMI) percentile via the CDCP's BMI percentile calculator which utilizes height, weight, age, and gender in its calculations.[59,134] All participants wore standardized footwear (Nike Pegasus) to control for the effect of footwear on running mechanics. Participant's leg length was measured bilaterally from the anterior superior iliac spine to the medial malleolus. Markers were placed on the anterior, posterior, and lateral portions of the shoe, lateral and medial malleolus, midway point of the tibia and fibula located between the knee and ankle, lateral and medial condyles of the knee, midway point of the femur location between the hip and knee, greater trochanter, anterior superior iliac spine, superior border of the iliac crest, and lumbosacral section of the spine (Figure 5). A five minute warm up that included light jogging and stretching was performed following placement of reflective markers. A static calibration trial was then collected while the participant stood on a single force platform in the center of the capture volume. Following static calibration, anatomical markers were removed from the participant leaving only the tracking markers on the participant during the movement trials. Next, participants ran across a 15 m ruHWay, embedded with a ground reaction force platform, at a given speed of 3.5 ± 5% m/s. Participants repeated the run 8-10 times with a minimum of one-two minutes of rest between trials. Trials were excluded and repeated if the participant: a) did not strike the force plate entirely with their dominant foot, b) ran outside of the accepted speed range during the set speed trials, c) adjusted their running mechanics based on force plate location, and/or d) sped up or slowed down while crossing the forceplate. Running speed was monitored using a photocell timing system.

Data Reduction

The CDCP's BMI percentile calculator was used to determine participant placement into the OV/OB or HW groups.[59] Participants classified ≥ 85th percentile were placed into the OV/OB group, while participants ≥ 5th and < 85th percentile were placed into the HW group.

Reflective markers were labeled then digitized using Qualisys Track Manager Software (Qualisys, Gothenburg, Sweden). The digitized markers were used to calculate joint motion using

Visual 3-D (C-Motion, Inc., Germantown, MD). Kinematic data was filtered with a recursive 4th order Butterworth filter at 5 Hz.[135] Kinematic variables of interest included sagittal and frontal plane joint excursions of the hip, knee and ankle joints. Excursions for early stance were calculated from foot strike to the peak values for each movement. Total joint excursion was calculated as the difference between the maximum and minimum joint angles during stance. Customized software (LabVIEW 8.0; National Instruments, Austin, TX) was used to extract the variables of interest from the motion files. The average of five trials was used for statistical comparisons for both self-selected and given speeds.

Ground reaction force data was filtered with a recursive 4th order Butterworth filter with a cutoff frequency of 50 Hz. Kinetic Variables of interest from the ground reaction force data during running included vertical impact peak, average vertical load rate, instantaneous vertical load rate, peak vertical force, and impulse. Ground reaction force variables are reported in both absolute values as well as values scaled to body weight.

Three-dimensional joint and segment angles were calculated with Visual 3-D software (C-Motion, Inc., Germantown, MD) using an *X*, *Y*, *Z* Euler angle rotation sequence.[120,136] Segment inertial properties were used to calculate internal joint moments and angular impulse.[126,137] Peak joint moments represents the max load at the joint, whereas angular impulse represents the total load experienced during stance and was calculated by multiplying the load with the length of time.[138] Joint moments and angular impulses were averaged over 5 trials and scaled to body weight. All variables of interest were calculated using a customized LabView™ (National Instruments Corporation, Austin, TX, USA) program.

Statistical Analysis

A one-way ANOVA was used to compare group differences for all variables of interest (with the exception of gender which a Chi-square test was used) using SPSS software (Version 22.0, IBM® SPSS® Statistics, Chicago, IL, USA). The 5 trials were averaged from each condition and calculated for each variable. Effect sizes were calculated utilizing Cohen's *d* with

0.2, 0.5 and 0.8 considered small, medium and large respectively.[139] Box plot analyses were used to identify and remove outliers. The level of significance was set at $p < 0.05$. Data were presented as means and standard deviation.

RESULTS

Demographics

Participant's gender, age, height, mass, and BMI percentile can be found in Table 1. The OV/OB group displayed significantly greater mass (OV/OB=51.86±10.6kg, HW=36.40±7.4kg; $p<0.001$) and BMI percentile (OV/OB=23.78±3.1, HW=17.25±1.7; $p<0.001$) when compared to the HW group.

Spatial-Temporal Variables

All participants ran between the given speeds of 3.3 and 3.68 m/s (3.5±5%) (OV/OB=3.47±0.04m/s, HW=3.49±0.04m/s; $p=0.21$). However, the time spent in stance was 24% longer for the OV/OB group compared to the HW group (OV/OB=0.37±0.13s, HW=0.29±0.10s; $p=0.03$). In addition, the OV/OB group displayed significantly shorter step lengths during running than the HW control group (OV/OB=0.74±0.07m, HW=0.79±0.07m; $p=0.026$). Both of these differences were associated with a moderate effect ($d=0.73$ and 0.72 respectively).

Ground Reaction Forces

Results of the ground reaction force variables scaled to body weight can be found in Table 2. Children classified as OV/OB displayed significantly greater peak vertical force when compared to HW children ($p=0.001$; $d=0.86$). However, vertical impulse, braking impulse, and propulsive impulse during the stance phase of running were significantly greater in the OV/OB group compared to the HW group ($p<0.05$; $d\geq0.67$). The OV/OB group displayed significantly greater vertical and horizontal loading when the absolute values of each of the ground reaction force variables are compared across the two groups. Absolute values of the ground reaction force variables can be found in Table 3. No other significant group differences were detected for ground reaction forces ($p>0.05$).

Joint Kinematics

Results of the sagittal and frontal plane joint excursion at the ankle, knee, and hip can be found in Figure 6. In the sagittal plane the HW group displayed greater knee and hip flexion excursions when compared to the OV/OB group ($p<0.05$; $d>0.74$). In the frontal plane, the HW group also displayed greater knee adduction excursions compared to the OV/OB group ($p=0.029$; $d=0.86$). However, the OV/OB group displayed significantly greater knee abduction excursions during early stance and greater ankle eversion excursions than the HW group ($p=0.035$; $d=0.71$). Furthermore, total ankle joint excursion in the frontal plane throughout stance was also significantly greater in the OV/OB group compared to the HW group ($p=0.038$; $d=0.70$). No other significant group differences were detected for the remaining joint kinematic variables of interest.

Joint Kinetics

Results of the peak joint moments and angular impulses can be found in Table 4. Results of the sagittal and frontal plane moments at the ankle, knee, and hip can be found in Figure 7.The results indicate that children who are classified as OV/OB display significantly greater max knee adduction and hip abduction moments than HW children ($p\leq0.019$; $d>0.90$). Hip abduction impulse was also significantly greater in the OV/OB children compared to the HW children ($p<0.001$; $d=1.40$). No other differences in peak moments or angular impulses were detected.

DISCUSSION

The purpose of this study was to compare running mechanics between children classified as OV/OB and children classified as having HW. Based on our results, it is evident that several kinematic and kinetic differences in running mechanics exist between these two groups of children.

Spatio-temporal Differences.

Even with both groups running the trials at the same speed, the OV/OB children displayed shorter step lengths and spent more time in the stance phase compared to the HW group of children. These findings are consistent with the findings of previous researchers who reported that obese children take shorter steps and spend more time in double support during walking.[119] da Silva-Hamu and colleagues explain that obese participants who walk with shorter step lengths do so in order to compensate for a reduction in joint range of motion.[140] A limited joint range of motion at the lower extremity joints during running would likely result in shorter step lengths. Another possible reason for the shorter step lengths would be a reduction in energy expenditure of the task. If less energy is expended per step when shorter steps are taken, then less muscle torque is needed to complete each step. Regardless of the amount of energy expended, in order for the runner to continue moving forward, they must create sufficient impulse on the ground to propel the body forward. This idea may help to explain the longer stance time. By increasing the time spent in stance, an OV/OB child would be able to create a larger impulse to the ground without increasing maximum force. It is possible that the OV/OB children in this study completed the running trials using shorter steps and spending more time in the stance phase in order to reduce energy expenditure and to compensate for a reduction in joint range of motion. More research is needed to definitively determine if this was the case for the OV/OB children in this study.

Ground Reaction Force Differences

The most notable of difference in running mechanics between the OV/OB and HW children are the absolute values for the ground reaction forces. Since OV/OB children have more mass than HW children, it would be expected that OV/OB children would display significantly greater absolute loading than HW children. However, by scaling ground reaction forces to body weight one makes the assumption that as body mass increases there is a proportionate increase in bone density, joint surface area and/or muscle mass to accommodate the increased load. However, researchers have reported that these changes do not occur proportionately.[35] In particular, lower extremity joint surface area has been reported to not increase proportionately to a child's body mass suggesting that obese children have smaller joint surface areas relative to their body weight. Greater absolute force distributed over a similar, or slightly larger joint surface area, would likely result in greater overall stress at that joint. It is therefore necessary to examine the absolute values of the ground reaction force variables when comparing OV/OB and MW children. As expected, the absolute values for the ground reaction force variables were all significantly greater for the OV/OB children compared to the HW children (Table 3). These data suggest that the OV/OB children in this study may have disproportionately greater loading at their joints.

Contrary to what we hypothesized no differences were detected for several of the ground reaction force variables when scaled to body weight. However, vertical, braking and propulsive impulses scaled to body weight were significantly greater for the OV/OB children. This was true even with the peak vertical force being significantly greater for the HW group. While comparing peak force gives researchers a good idea of how high the force is at a particular portion of stance, investigating the children's impulse throughout stance may provide researchers a better idea of the impacts OV/OB children may be experiencing throughout the entirety of the stance phase of the run. Subsequently, these data suggest that the OV/OB group require a greater impulse to move their more massive body. The longer time spent in stance appears to be a major contributor to the larger impulses displayed by the OV/OB children. Furthermore, the greater impulses also suggest that although peak force is the same or higher in the HW children, the force is being applied for a longer period of time in the OV/OB children potentially resulting in greater overall force during the stance phase of running. The higher absolute vertical loading and the larger impulses (both absolute and scaled to body weight) is further evidence of the greater vertical loading displayed by the OV/OB children. Increased vertical loading during running has been associated with several running related injuries including tibial stress fractures, iliotibial band syndrome and patellofemaoral pain syndrome.[111,120] Furthermore, increased vertical loading has been associated with the development of joint degenerative diseases such as osteoarthritis. Alternative exercises that have lower vertical loading may need to be recommended for children classified as OV/OB.

Differences joint kinematics

The adjustments made by OV/OB children may be explained by the significantly decreased amount of flexion excursion occurring at the knee. In addition, the OV/OB children are running with significantly less flexion at the knee throughout stance (p=0.026) and at the hip during early stance (p=0.015) when compared to HW children. The lack of flexion may be due to a decreased range of motion at the lower extremity joints which may be related to the increased amount of adiposity. If the children are unable to reach a higher degree of flexion during high impact activities, such as running, their body may not absorb as much shock as the body of someone who goes into greater flexion.

Differences in the frontal plane could have even greater implications. OV/OB children's significantly greater eversion at the ankle during early stance (p=0.035) and abduction at the knee (p=0.029) may put the child at risk for greater issues. Given the increased loading experienced by OV/OB children, if the loading is occurring unevenly at the joint, the child's risk for lower extremity mal-alignments may be increased. Furthermore, if a mal-alignment forms due to the increased joint stress the obese child may start experiencing issues at the surrounding joints, such as the hip, to counteract the uneven stress. This counteracting effect could be why obese children have a higher prevalence of musculoskeletal problems, including slipped capital femoral epiphysis.[87,92] If a mal-alignment is left uncorrected, the obese child could have negative impacts throughout life which includes a higher risk of suffering from a joint degenerative disease, such as osteoarthritis, and/or needing surgery.

Differences in joint kinetics

One of the biggest indicators of the amount of joint loading is the net joint moment. Greater net moments at a given joint have been associated with increased compressive stress at that joint. Furthermore, higher than normal frontal plane joint moments at the hip and knee during running have been linked to overuse running injuries as well as knee osteoarthritis.[138,141,142] Both peak knee adduction moments and peak hip abduction moments were significantly greater in the OV/OB children compared to HW children. In addition, the OV/OB children also displayed significantly greater hip abduction angular impulse suggesting that the overall joint loading at the hip is much greater throughout the entire stance phase. The greater knee adduction moments, hip abduction moments, and hip abduction angular impulse displayed by the OV/OB group in this study provides further evidence of increased loading at the hip and knee joints for the OV/OB children.

Conclusion

Several differences in running mechanics are present between OV/OB and HW children. Among the most notable are the higher ground reaction forces and frontal plane joint moments which may result in greater joint loading, mal-alignments, and potential joint pathologies. Encouraging participation in physical activity is crucial in reducing childhood obesity rates. Equally as important is prescribing appropriate exercise that do not place a child at an increased risk for developing other types of injuries or pathologies associated with excessive loading or mal-alignments. Progression from low- to high-impact activities may give the bone and muscle time to adjust to the loads as they increase, potentially reducing and ideally eliminating the OV/OB children's increased risk of pain and injury. Creating a positive association with physical activity is important at a young age. By reducing a child's risk of pain and/or injury during physical activity, we can increase the likelihood that they will enjoy and be willing to engage in physical activity throughout their life.

LIMITATIONS

A study limitation was the lack of physical activity and sedentary time data from participants. Since a child's daily activity or lack thereof, can greatly influence how their body adapts to daily loading, knowing the child's activity level could give further insight into how running, regardless of weight, may impact the lower extremity joints. A second limitation of the study was the grouping of overweight and obese children into a single category. This grouping method may be too diverse depending on if the children in the overweight group had a higher or lower BMI within their given classification. A third limitation was the study did not determine joint loading of the participants. Without joint loading, researchers cannot definitely say how the differences in running mechanics between the HW and OV/OB group are influencing the lower extremity joints. Lastly, the given running speed required by the children may have given an advantage to the HW group, as these children were able to achieve the speed with more ease than the OV/OB group was able to do so.

FIGURES

Figure 5: Example of reflective marker set placement

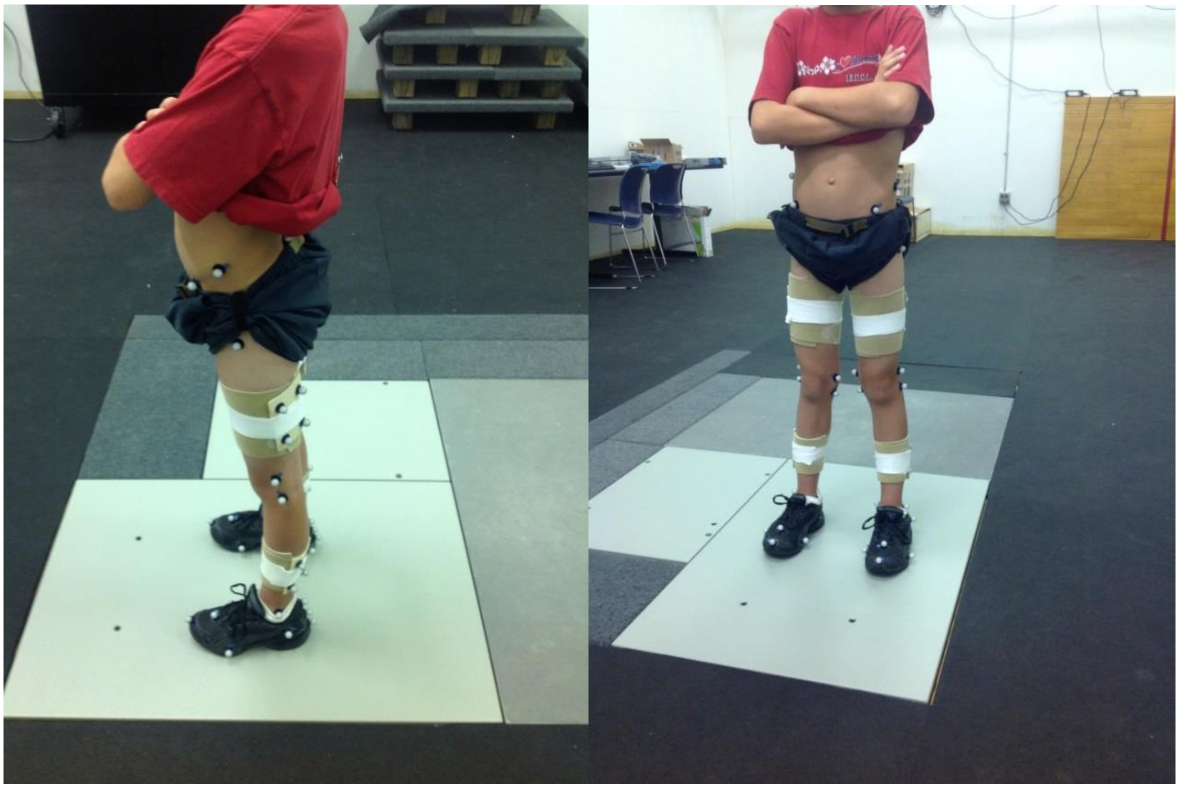


Figure 6: Sagittal (a, b, c) and frontal (d, e, f) plane joint excursion for ankle, knee, and hip joints throughout stance

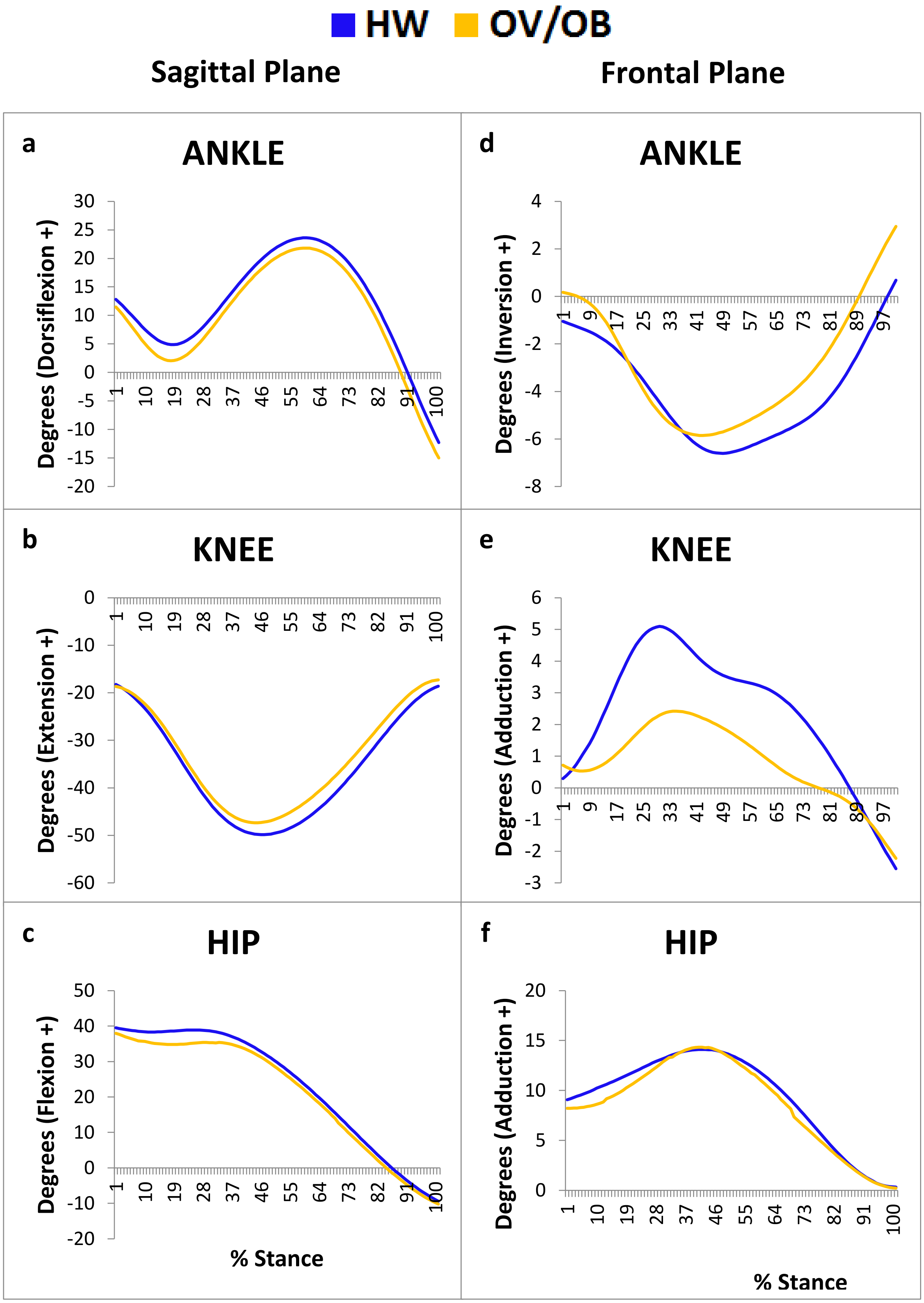
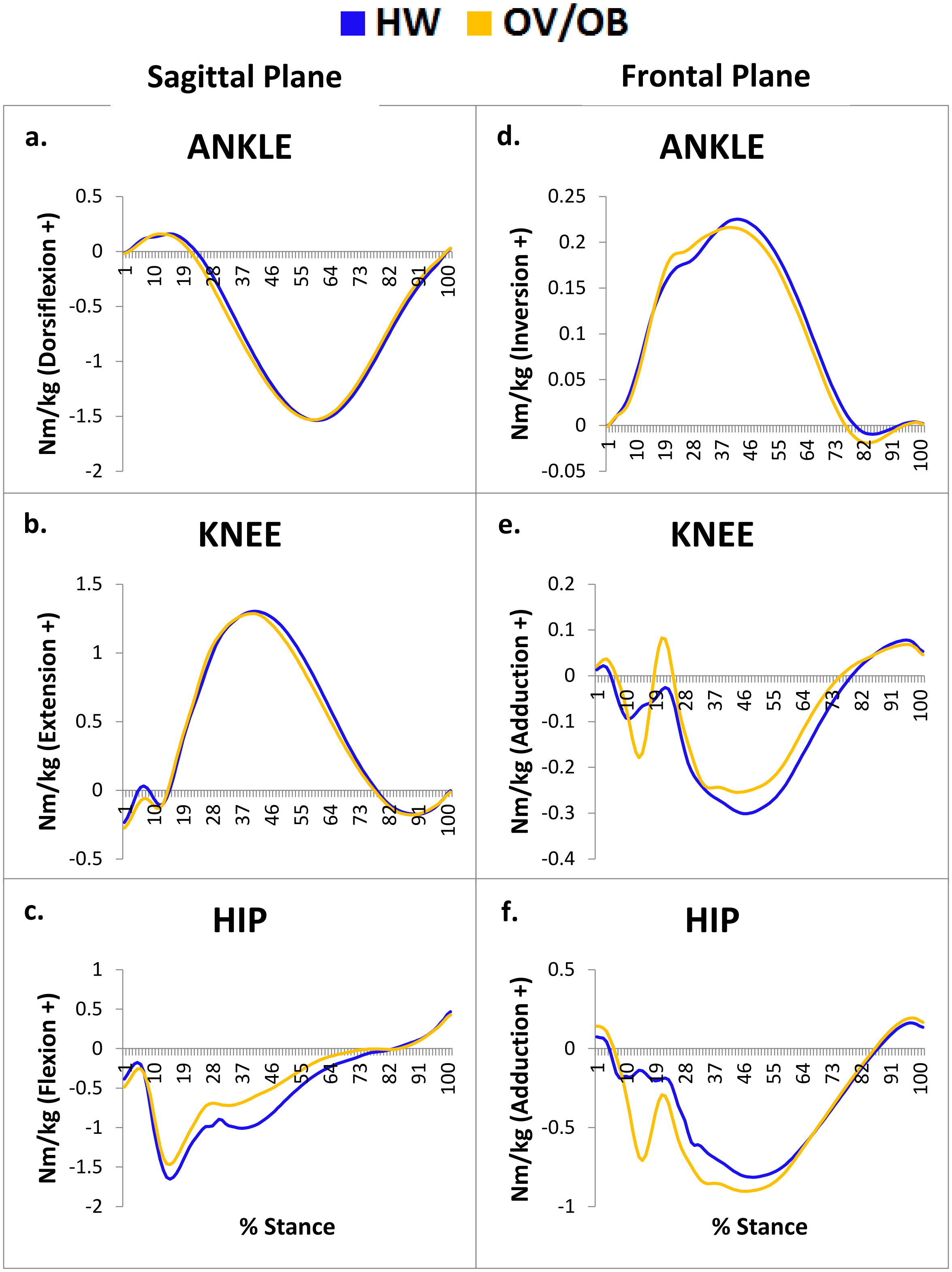


Figure 7: Sagittal (a, b, c) and frontal (d, e, f) plane moments for ankle, knee, and hip joints throughout stance.



TABLES

Table 1: Participant demographics

	HW	OV/OB	Sig (2-tailed)
Gender	M=12, F=13	M=8, F=9	0.42
Age	9.84±1.3	10.18±1.3	0.33
BMI Percentile	17.25±1.7	23.78±3.1	<0.001*
Height	1.44±0.1	1.47±0.1	0.26
Mass	36.40±7.4	51.86±10.6	<0.001*

*Indicates a significant difference between groups (p<0.05)

Table 2: Mean±SD, *p*-values, and effect sizes (Cohen's *d*) for ground reaction force variables scaled to body weight (BW) for the healthy weight (HW) and overweight/obese (OV/OB) groups.

Variables	**HW**	**OV/OB**	***p*-value**	***d***
Peak Vertical Force (BWs)	2.57±0.23	2.40±0.18	0.011*	0.86
Vertical Impulse (BWs)	0.35±0.05	0.52±0.17	0.001*	1.42
VIP(BW)	1.74±0.41	1.88±0.41	0.29	
VILR (BW/s)	70.8±25.7	74.3±32.7	0.71	
VALR (BW/s)	59.1±22.1	60.5±29.1	0.95	
Braking Impulse (BWs)	-0.02±0.01	-0.03±0.01	0.007*	0.97
Propulsive Impulse (BWs)	0.03±0.01	0.04±0.01	0.04*	0.67
Peak Braking Force (BWs)	-0.33±0.06	-0.34±0.05	0.69	
Peak Propulsive Force (BWs)	0.32±0.03	0.31±0.03	0.45	

*Indicates a significant difference between groups (p<0.05)

Table 3: Mean±SD, *p*-values, and effect sizes (Cohen's *d*) for absolute ground reaction force variables for the healthy weight (HW) and overweight/obese (OV/OB) groups.

Variables	**HW**	**OV/OB**	***p*-value**	***d***
Peak Vertical Force (N)	927.8±45.1	1209.2±48.7	<0.001*	5.99
Vertical Impulse (N)	118.4±6.40	266.3±25.9	<0.001*	7.83
VIP(N)	620.2±40.4	952.7±68.6	<0.001*	5.91
VILR (N/s)	24909.0±2220.5	37934.4±4786.5	0.02*	3.49
VALR (N/s)	21034.1±1826.0	30992.3±4237.0	0.04*	3.05
Braking Impulse (Ns)	-7.5±0.79	-15.1±1.57	<0.001*	6.14
Propulsive Impulse (Ns)	10.1±1.07	17.9±1.80	0.04*	5.26
Peak Braking Force (Ns)	-119.0±5.89	-171.6±9.86	<0.001*	6.48
Peak Propulsive Force (Ns)	115.5±5.82	156.6±7.09	0.001*	6.32

*Indicates a significant difference between groups (p<0.05)

Table 4: Mean±SD, *p*-values, and effect sizes (Cohen's *d*) for peak joint moments and angular impulse variables for the HW and OV/OB groups.

Variables	**HW**	**OV/OB**	***p*-value**	***d***
Dorsiflexion Moment	0.23±0.08	0.21±0.06	0.375	
Plantarflexion Moment	-1.59±0.17	-1.55±0.15	0.550	
Dorsiflexion Angular Impulse	0.01±0.00	0.01±0.00	0.265	
Plantarflexion Angular Impulse	-0.15±0.03	-0.16±0.01	0.154	
Inversion Moment	0.24±0.07	0.24±0.06	0.846	
Eversion Moment	-0.01±0.01	-0.01±0.01	0.101	
Inversion Angular Impulse	0.02±0.01	0.03±0.01	0.783	
Eversion Angular Impulse	-0.00±0.00	-0.00±0.00	0.155	
Knee Extension Moment	1.38±0.21	1.34±0.12	0.450	
Knee Flexion Moment	-0.30±0.09	-0.31±0.07	0.610	
Knee Extension Angular Impulse	0.12±0.04	0.12±0.02	0.673	
Knee Flexion Angular Impulse	-0.01±0.00	-0.01±0.01	0.213	
Knee Adduction Moment	0.10±0.06	0.17±0.10	0.019*	0.90
Knee Abduction Moment	-0.37±0.12	-0.39±0.22	0.752	
Knee Adduction Angular Impulse	0.01±0.00	0.01±0.00	0.766	
Knee Abduction Angular Impulse	-0.03±0.02	-0.03±0.02	0.482	
Hip Extension Moment	-1.91±0.32	-1.67±0.41	0.054	
Hip Flexion Moment	0.03±0.08	0.01±0.13	0.623	
Hip Extension Angular Impulse	-0.13±0.03	-0.11±0.04	0.077	
Hip Flexion Angular Impulse	0.01±0.00	0.01±0.01	0.347	
Hip Adduction Moment	0.18±0.11	0.16±0.12	0.512	
Hip Abduction Moment	-0.87±0.19	-1.05±0.16	0.003*	1.06
Hip Adduction Angular Impulse	0.01±0.00	0.01±0.00	0.145	
HIp Abduction Angular Impulse	-0.09±0.02	-0.11±0.02	0.000*	1.40

*Indicates a significant difference between groups (p<0.05)

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