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Effects of Obesity on Knee Extensor Structure, Function, and Gait: A Systematic Review and Meta-Analysis

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EFFECTS OF OBESITY ON KNEE EXTENSOR STRUCTURE, FUNCTION, AND

GAIT: A SYSTEMATIC REVIEW AND META-ANALYSIS

by

Michael N. Vakula

A dissertation submitted in partial fulfillment
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of

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in

Disability Disciplines

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ABSTRACT

Effects of obesity on knee extensor structure, function, and gait: a systematic review and
meta-analysis

by

Michael N. Vakula, Doctor of Philosophy

Utah State University, 2022

Major Professor: Eadric Bressel, Ph.D.
Department: Kinesiology and Health Science

Defined as an abnormal or excessive fat accumulation that can impair health,

obesity is a common, costly, and critical disease that increases the risk of co-morbidities,

disability, and premature death. Most commonly, obesity is caused through a positive

energy balance, brought on through increased consumption of energy dense foods and

decreased time spent physically active. The greater weight with obesity interrupts normal

musculoskeletal function which can lead to physical maladaptation's such as increased

incidence of lower-extremity muscle dysfunction and abnormal gait patterns, both of

which are among top risk factors for falls in older individuals. However, the effects of

obesity on gait and lower-extremity muscle function have not been formally quantified by

integrating the results of all studies in a systematic review and meta-analysis. Therefore,

the purpose of this dissertation was to (1) determine the effect of obesity on

spatiotemporal measures of gait in adults, and to (2) determine the effect of obesity on

knee extensor structure and function in children, adolescents, adults and older adults. In

the first study, there were 47 studies included in the systematic review and 44 in the

meta-analyses. Study two included 35 studies in the systematic review and 29 in the

meta-analyses. The results suggested that (1) obesity decreases self-selected walking

speed ($d_{pooled} = -1.03$, P = <0.001) and step length ($d_{pooled} = -0.95$, P = <0.001), but

increases step width ($d_{pooled} = 1.04$, P = <0.001) and the double support period ($d_{pooled} =$

1.86, P = 0.003), and (2) obesity increases absolute maximal measures of knee extensor

function ($d_{pooled} = 1.33$, P = <0.001) and muscle size ($d_{pooled} = 2.69$, P = <0.030), but

decreases relative maximal measures of knee extensor function ($d_{pooled} = -0.48$, P =

<0.042) and muscle quality ($d_{pooled} = -2.50$, P = 0.001). However, some of these effects

appears to diminish with aging. The results of this dissertation will improve our

understanding of how obesity influences gait and knee extensor function, which will

allow for the design of better treatments for those suffering from obesity as well as serve

as a basis of knowledge to guide researchers going forward.

(142 pages)

PUBLIC ABSTRACT

Effects of obesity on knee extensor structure, function, and gait: a systematic review and meta-analysis

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Michael N. Vakula

Obesity is a common, costly, and critical disease that increases the risk of disability and premature death. Most commonly, obesity is caused by an increased consumption of energy dense foods and decreased time spent being physically active. The greater weight with obesity interrupts normal musculoskeletal function which can lead to physical adaptations such as decreased lower-extremity muscle strength and abnormal walking patterns, both of which are among top risk factors for falls in older individuals. However, the effects of obesity on walking and lower-extremity muscle strength have not previously been examined by incorporating the results of all existing studies in a comprehensive systematic review and meta-analysis. Therefore, the purpose of this dissertation was to (1) determine the effect of obesity on measures of walking in adults, and to (2) determine the effect of obesity on knee extensor strength, muscle size, and muscle quality in children, adolescents, adults and older adults. In the first study, there were 47 studies included in the systematic review and 44 in the meta-analyses. Study two included 35 studies in the systematic review and 29 in the meta-analyses. The results suggest that (1) obesity reduces self-selected walking speed and step length, but increases step width and the amount of time spent with both feet in contact with the ground, and (2) obesity increases absolute maximal measures of knee extensor strength

and muscle size, but decreases relative maximal measures of knee extensor strength and muscle quality. However, the effect of obesity on knee extensor size, quality, and strength appears to diminish with age. The results of this dissertation will improve our understanding of how obesity influences walking and knee extensor function, which will allow the design of better treatments for those suffering from obesity as well as a basis of knowledge to guide researchers going forward.

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CHAPTER I

INTRODUCTION

Background

Defined as an abnormal or excessive fat accumulation that can impair health, obesity is a largely preventable disease that can increase the risk of disability, non-communicable diseases, and premature death (CDC, 2021a; WHO, 2021). Generally, adults are classified as obese if they have a body mass index (BMI) (kg/m^2) of 30 or greater. Globally, 650 million individuals were classified as obese in 2016, and in the United States, the prevalence of adult obesity was over 40% in a 2018 estimate (Hales, 2020). As the prevalence of obesity continues to rise, so do medical costs. The annual medical cost of obesity in 2016 was estimated at $126 billion in the United States, with individuals with obesity spending an additional $1028 to $2718 per person per year compared to individuals with normal weight (van den Broek-Altenburg et al., 2022).

Typically, obesity is caused by consuming more calories than are utilized, creating a positive energy imbalance commonly caused by decreased physical activity and increased consumption of energy dense foods. This unbalanced energy surplus is stored as body fat (i.e., adipose tissue) and as it increases, so does the risk of comorbidities such as diabetes, cancer, cardiovascular disease, and musculoskeletal disorders (WHO, 2021). Moreover, obesity inhibits normal musculoskeletal function, which commonly results in altered lower-extremity muscle structure and function,

aberrant gait biomechanics, decreased mobility, and instability compared to those without obesity (Bergland et al., 2000; Fabris et al., 2006; Vakula et al., 2019; Zecevic et al., 2006).

The structure (i.e., size and quality) and contractile function (i.e., force, velocity, and power characteristics) of skeletal muscle are altered in individuals with obesity. The majority of the literature suggests absolute strength (i.e., the maximum force or torque a muscle can generate) and power (i.e., the ability of a muscle to generate torque or force quickly) of anti-gravitational muscles such as the knee extensors are greater in individuals with obesity compared to those without (Garcia-Vicencio et al., 2016; Hulens et al., 2001; Maffiuletti et al., 2007). Conversely, when these measures are normalized to body mass or fat-free mass, the strength and power of lower-extremity muscles are reduced by up to 40% in individuals with obesity in comparison to individuals without obesity, indicating that obesity may impair the contractile capabilities of muscle tissue (Abdelmoula et al., 2012; Blimkie et al., 1990; Choi et al., 2016; Hulens et al., 2001; Lafortuna et al., 2005; Maffiuletti et al., 2007; Tsiros et al., 2013; Vakula et al., 2019). Relative measures of contractile function are of particular importance to the functioning of individuals with obesity, considering that the muscular forces needed to produce and control movement during activities of daily living (e.g., walking) increase with body mass. While the exact mechanisms behind the impaired contractile function experienced by individuals with obesity are unknown, altered skeletal muscle structure likely plays a role.

In individuals with obesity, the size of anti-gravitational muscles is greatly increased (Choi et al., 2016; Hulens et al., 2001; Tsiros et al., 2013; Vakula et al., 2019).

For instance, the anatomical cross-sectional area of the knee extensors and plantar flexors are up to 50% larger in individuals with obesity compared to those without (Garcia-Vicencio et al., 2016; Vakula et al., 2019). However, despite having larger muscles, the skeletal muscle quality (i.e., echo intensity grey scale, strength per unit of size, muscle tissue fat content) appears to be reduced in individuals with obesity (Arieta et al., 2022; Giuliani et al., 2020; Herda et al., 2018; Rastelli et al., 2015; Vakula et al., 2019). For example, the intermuscular fat volume of the knee extensors is three times greater in individuals with obesity than controls (Choi et al., 2016). This is important, considering greater lipid accumulation is associated with lower force production in skeletal muscle fibers (Choi et al., 2016). This decrease in contractile function is due in part to the increased concentration of intramuscular fat in individuals with obesity (Goodpaster et al., 2000; Malenfant et al., 2001). Increased levels of intramuscular fat have been shown to increase the stiffness of the base material properties of the muscle, which has a negative effect on force production (Rahemi et al., 2015). Furthermore, lower knee extensor muscle quality measured indirectly via ultrasound echo intensity is associated with a lower internal knee extension moment (i.e. quadriceps avoidance) while walking at a self-selected speed in individuals with obesity (Vakula et al., 2019). The findings above indicate that skeletal muscle structure is altered with obesity and is also associated with the aberrant gait mechanics familiar to individuals with obesity.

In response to a high body mass and altered muscle structure and function, individuals with obesity may alter their gait patterns. For example, a slower self-selected gait speed, increased single and double limb support time, and shorter but wider steps are commonly reported in individuals with obesity compared to those without (Freedman

Silvernail et al., 2013; Jegede et al., 2017; Lai et al., 2008; Vakula et al., 2019; Vismara et al., 2006). Together, these gait pattern adaptations are thought of as a strategy to improve postural stability and reduce ground reaction forces that may overload weight-bearing joints (i.e., knee joint) (Vakula et al., 2019, 2022). For example, the slow and steady gait pattern employed by individuals with obesity produces a comparable level of instantaneous stability to normal-weight individuals at self-selected walking speed (Liu & Yang, 2017). Moreover, net knee muscle moments can be reduced by approximately 40% when individuals reduce their walking speed from 1.4 m/s to 1.0 m/s (Browning & Kram, 2007). Yet, a lesser self-selected walking speed reduces an individual's mobility and may be an indication of a mobility disability (Abellan Van Kan et al., 2009).

Although weight loss is the optimal solution to combat the effects of obesity, long term weight loss interventions are unsuccessful (Barte et al., 2010). The real world complexity of why people gain weight and keep it on, make weight loss a difficult target. Thus, there is a need to better understand the difficulties of obesity and interventions other than weight loss that combat the effects of obesity. Currently, studies reporting the effects of obesity on gait and lower-extremity muscle structure and function are limited, and their results lack consistency. For example, some authors reported that self-selected walking speed was reduced (Freedman Silvernail et al., 2013; Vakula et al., 2019) and knee extensor peak torque was increased with obesity (Choi et al., 2016; Hulens et al., 2001), while others have reported no effect of obesity on either measure (Milner et al., 2018; Rolland et al., 2007; Vakula et al., 2019). Efforts have been made to review the effects of obesity on gait and muscle structure and function (Bollinger, 2017; Del Porto et al., 2012; Hills et al., 2002; Maffiuletti et al., 2013; Wearing et al., 2006), yet, to the best

of our knowledge, no study has attempted to quantify the effect of obesity using a systematic review and meta-analysis. Therefore, a current and reliable understanding of the effects of obesity on gait and lower-extremity muscle structure and function is not well understood.

Objectives

The primary purpose of this dissertation was to review the existing evidence and analyze the pooled effects of obesity on spatiotemporal gait measures and knee extensor structure and function. To address these aims, a series of related studies was conducted and presented as individual chapters that are described below:

Chapter 2: Spatiotemporal gait characteristics in adults with obesity: A systematic review and meta-analysis

Objective: To compare spatiotemporal gait characteristics between adults with and without obesity.

Chapter 3: Knee extensor structure & function in children, adolescents, adults, and older adults with obesity: A systematic review and meta-analysis

Objective: To quantify the effect of obesity on knee extensor structure and function in children, adolescents, adults, and older adults in comparison to normal-weight counterparts.

Structure of Dissertation

This dissertation is composed of two systematic reviews with meta-analyses. Chapter 2 consists of a systematic review with meta-analysis examining the effects of obesity on spatiotemporal measures of gait in adults. Chapter 3 consists of a systematic review with meta-analysis intended to assess the effects of obesity on knee extensor structure and function in children, adolescents, adult, and older adults. Chapter 4 presents a summary of the findings from the two systematic reviews with meta-analysis, their practical applications, and future directions for research are provided.

CHAPTER II

SPATIOTEMPORAL GAIT CHARACTERISTICS IN ADULTS WITH OBESITY: A SYSTEMATIC REVIEW AND META-ANALYSIS

Abstract

Purpose: To systematically review and analyze the effect of obesity on spatiotemporal gait characteristics in adults.

Methods: Experimental studies published in the English language examining spatiotemporal measures of gait in adults aged 18 – 55 years with obesity or normal weight were considered. A search for prospective studies were performed in four electronic databases (PubMed, CINAL, Scopus, Cochrane Library), last searched on February 2nd, 2022. Risk of bias among the included studies was assessed using a modified epidemiological appraisal instrument consisting of 30 questions across five domains: study description, subject selection, measurement quality, data analysis, generalization of results. Data were extracted and meta-analyzed using a random effects model for primary outcomes (self-selected walking speed, step length, step width, cadence, stance period, and double support period).

Results:

   Included Studies: The database search resulted in 4536 unique entries, 47 were included in the systematic review, and 44 in the meta-analyses.

Synthesis of Results: Obesity reduces self-selected walking speed (d_{pooled}= -1.03, P = <0.001) and step length at self-selected walking speed (d_{pooled} = -0.95, P = <0.001), but increases step width at self-selected walking speed (d_{pooled} = 1.04, P = <0.001) and double support period at self-selected (d_{pooled} = 1.86, P = 0.003) and standardized gait speeds (d_{pooled} = 4.91, P = 0.044).

Discussion: This systematic review and meta-analysis provides support that obesity decreases self-selected walking speed and step length at self-selected walking speed, but increases step width at self-selected walking speed and the double-support period at self-selected and standardized walking speeds. The slower and more stable gait pattern adopted by individuals is likely a strategy to limit metabolic cots, reduce joint loading, and improve dynamic stability while walking, which comes at the cost of mobility. Interventions geared at the treatment and management of obesity should consider and attend to such alterations for best practice. Finally, there are a limited number of studies reporting on spatial-temporal gait characteristics in individuals with obesity. More research is needed to better understand the effects of obesity on gait.

Registration: This systematic review and meta-analysis was prospectively registered in the Open Science Framework Registries (DOI: 10.17605/OSF.IO/EA4NW).

Introduction

Obesity is a common, costly, and critical disease that increases the risk for other noninfectious health conditions, disability, and premature death. Generally, obesity is defined as an abnormal or excessive fat accumulation that can impair health (WHO, 2021). Obesity is also defined as a body mass index (kg/m^2) of 30 or greater (CDC, 2021a; WHO, 2021). Worldwide, 650 million people were considered obese as of 2016, a number that has seen an approximate increase of 300% since 1975 (WHO, 2021). In the United States, the prevalence of adult obesity increased approximately 12% from 2000 to 2018, and as of 2018 the prevalence of obesity was 42.4% (Hales, 2020). In 2008 the annual medical cost of obesity was estimated at $147 billion, and individuals with obesity spent 42% more or an additional $1,429 per capita on medical expenses compared to individuals with normal weight in the United States (Finkelstein et al., 2009).

The root cause of obesity is a positive energy imbalance created by consuming more calories than are being expended. Globally, this shift in the energy balance is likely due to an increase in energy-dense foods and a decreased amount of time spent being physically active. Importantly, the risk for noncommunicable diseases increases with body mass index, and obesity is a considerable risk factor for comorbidities such as cardiovascular disease, diabetes, cancer, and musculoskeletal disorders (WHO, 2021). Obesity is best managed non-surgically or pharmacologically through the combination of diet and exercise (Chin et al., 2016). Walking is one of the most commonly prescribed modes of exercise for individuals with obesity. However, the greater weight from obesity interferes with normal musculoskeletal function causing physical adaptations such as

increased incidence of lower-extremity muscle dysfunction, impaired balance, and abnormal walking or gait patterns (i.e., biomechanics) (Bergland et al., 2000; Fabris et al., 2006; Vakula et al., 2019; Zecevic et al., 2006), all of which are among top risk factors for falls in older individuals.

Gait adaptations common to obesity include a reduced self-selected walking speed, increased single and double limb support time, a shorter step length, and increased step width (Freedman Silvernail et al., 2013; Jegede et al., 2017; Lai et al., 2008; Vakula et al., 2019; Vismara et al., 2006). These gait adaptations are considered a strategy used by individuals with obesity to improve postural stability in response to an underlying imbalance; and a strategy to minimize the effect of ground reaction forces that may overload weight-bearing joints and contribute to osteoarthritis. For example, it has been proposed that if individuals with obesity reduce their walking speed from 1.4 m/s to 1.0 m/s, net knee muscle moments would be reduced by approximately 40% (Browning & Kram, 2007). Likewise, the slower and stable gait pattern implemented by individuals with obesity results in a similar level of instantaneous stability (i.e., the shortest distance from an instantaneous center of mass (COM) state to all interpolated points on the stability boundary in the COM position-velocity space) in comparison to normal-weight individuals walking at self-selected pace (Liu & Yang, 2017).

The current data regarding the effects of obesity on gait biomechanics is limited, and the reported outcome measures in the studies lack consistency, making it difficult to analyze the pooled effects of obesity. Of the studies reporting on the effects of obesity on walking biomechanics, spatiotemporal gait measures are the most commonly reported. However, the current literature regarding the effects of obesity on spatiotemporal gait

measures lacks clarity. For example, some authors report that self-selected walking speed is reduced in individuals with obesity (Freedman Silvernail et al., 2013; Vakula et al., 2019), whereas others report no difference in self-selected walking speed between individuals with or without obesity (Błaszczyk et al., 2011; Milner et al., 2018). Recently, efforts have been made to review the effects of obesity on gait (Del Porto et al., 2012; Hills et al., 2002; Wearing et al., 2006). However, no study to our knowledge has attempted to quantify the effect of obesity on gait biomechanics by integrating the results of all studies that include spatiotemporal gait measures in a systematic review and meta-analysis. Policymakers, healthcare professionals, and scientists worldwide serve to benefit from current and reliable data for developing interventions designed to offset the burden of obesity. Thus, an improved understanding of the pooled effects of obesity on spatiotemporal measures of gait is needed to better understand the effect of obesity on these parameters and serve as a guide for researchers to improve gait and obesity related research in the future.

The objective of this systematic review and meta-analysis was to evaluate the effect of obesity on commonly reported measures of gait such as self-selected walking speed, step length, step width, cadence, and stance and double support period. Specifically, our aim was to review experimental studies that assessed the aforementioned spatiotemporal measures of gait at self-selected and standardized walking speeds in adults 18-55 years old with and without obesity. The findings of this study will improve the identification of gait abnormalities in individuals with obesity and thus improve the efficacy of disease management.

Methods

This study was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-analysis statement (Moher et al., 2009). In order to minimize bias in the decision-making process of our review methods, this systematic review and meta-analysis was prospectively registered in the Open Science Framework Registries (DOI: 10.17605/OSF.IO/EA4NW).

Eligibility Criteria

The following criteria were used to assess studies for eligibility to be included in the review and meta-analyses:

- *Types of studies*: Experimental studies (i.e., cross-sectional, randomized control trials) published in the English language that examine spatiotemporal measures of gait in individuals with obesity and individuals with normal weight were considered. No restrictions were placed on publication date. Only baseline data from randomized control trials were included in the meta-analyses.

- *Types of participants*: Adults aged 18-55 years old with either obesity or normal weight were considered for inclusion. In alignment with the definition set by the Center for Disease Control and the World Health Organization, individuals with obesity were defined as those with a BMI greater than 30 and subdivided into Class I 30 to < 35, Class II 35 to < 40, Class III 40+ categories. Conversely, those with normal weight were defined by a BMI of 18.5-24.9. Individuals with

cognitive dysfunction, sensory impairments, or physical disabilities were excluded from this review as they are known to alter spatiotemporal measures of gait (Constantinou et al., 2014; Creaby & Cole, 2018).

- *Types of interventions*: Studies that compare spatiotemporal measures of gait at either self-selected or standardized walking speeds.
- *Types of outcome measures*: Primary outcome measures include: self-selected walking speed, and step length, step width, cadence, and stance and double support period at both self-selected and standardized speeds.

Information Sources

Two researchers (M.V. and Y.K.) working independently of one another identified studies by searching the following electronic databases: PubMed (MEDLINE), CINAL (EBSCO), Scopus, and Cochrane Library from the commencement of the study through February 3rd, 2022. The reference lists of related articles were manually reviewed to spot any studies that were not identified by the systematic searches.

Search

The following search items were used to search the electronic databases: (walk* OR gait OR locomot* OR ambulat* OR biomechanic*) AND (speed* OR velocity* OR cadence OR 'step length' OR 'stride length' OR stance OR swing OR spatiotemporal OR spatial OR temporal OR spatial-temporal) AND (overweight OR obes* OR 'body mass index OR BMI OR fat).

Study Selection

Eligibility assessment were performed independently by two reviewers (M.V. and Y.K.) in a standardized and unblended manner. Disagreements that arose between reviewers were resolved with a meeting in which the articles in question were discussed until an agreement between reviewers was reached.

Data Collection Process

Data were extracted independently by two researchers (M.V. and Y.K.). All data were collected using a custom Microsoft Excel document that has previously been pilot-tested on 12 related studies and refined accordingly. Authors of the included studies were not asked for additional data as only published information sources were included in the analysis.

Data Items

Data were extracted from each of the included studies on (1) participant characteristics (sample size, age, sex, body mass index); (2) type of intervention (walking surface, footwear, gait analysis instrumentation, data normalization); (3) type of outcome measure (self-selected gait speed, and step or stride length, step width, cadence, single-limb and double limb support period at either self-selected or standardized speed).

Risk of Bias in Individual Studies

The methodological quality of eligible studies were evaluated by a modified epidemiological appraisal instrument (EAI) created by Genaidy et al.,(Genaidy et al.,

2007). The original instrument consists of 43 items across five domains: study description, subject selection, measurement quality, data analysis, generalization of results. Similar to a previous review and meta-analyses (Lawrenson et al., 2019), the EAI was modified from 43 down to 30 criteria of the highest importance for the included studies (Appendix A). Each item was scored as "Yes" (score of 2), "Partial" (score of 1), "No" (score of 0), "Unable to determine" (score of 0), or "Not applicable" (item excluded). The appraisal instrument has demonstrated good to excellent validity and inter-rater reliability (Kappa coefficient = 90% [CI; 87 to 92%]) (Genaidy et al., 2007). Two independent assessors (M.V. and Y.K.) blinded to the author and details of the publication assessed each study. A consensus meeting was held to reach an agreement between assessors on any disagreements. The agreement level between assessors' scores was calculated using the Cohen kappa statistic for each question (Viera & Garrett, n.d.). Overall study quality was based on the average score across each item, with a maximum possible score of 2.0. Studies were further classified as high quality (≥1.4), moderate quality (1.1 to <1.4), or poor quality (<1.1)(Genaidy et al., 2007).

Summary Measures

The primary outcome measures were the standardized mean differences in spatiotemporal gait measures comparing individuals with obesity to those with normal weight.

Planned Methods of Analysis

The means and standard deviations for each outcome measure were extracted and entered into RevMan 5.4 software (Cochrane), from which standardized effect sizes (Cohen d), the corresponding effect size standard error, and 95% confidence intervals were calculated. Standardized rather than fixed effect sizes were calculated as they are unitless and account for differences between studies. When spatiotemporal measures of gait were reported across a range of conditions (i.e., different gait speeds), a single study-wise effect size was calculated using a fixed-effects model in which the condition-wise effect sizes was weighted by their inverse variances (Constantinou et al., 2014; J. Higgins et al., 2021). A fixed-effects model was selected as we expected a common effect of obesity on outcome measures within a study. If data were presented as a figure rather than in a table, the data was digitized using ImageJ software (National Institutes of Health, Bethesda, MD).

Overall pooled effect sizes, 95% confidence intervals, and heterogeneity statistics were calculated using JASP (Version 0.16.3) for each of the spatiotemporal outcomes using a random-effects model with a restricted maximum likelihood approach (Harville, 1977). A random-effects model was selected due to the variability in experimental factors (i.e., self-selected walking speed, BMI group, gait analysis instrumentation, etc.). Heterogeneity level was categorized as: 0-25%= low, 26-50% = moderate, 51-100% = high (J. P. T. Higgins et al., 2003). Self-selected and standardized gait speed outcomes are presented on separate forest plots to aid in visual examination of the data.

Risk of Bias Across Studies

The risk of publication bias were assessed visually using funnel plots and statistically using Egger's test (Egger et al., 1997).

Additional Analyses

In order to examine if the outcome effects vary in relation to the severity of obesity (i.e., Class I, II, or III), a subgroup analysis was conducted.

Results

Literature Search

The search of the four databases resulted in 4536 unique entries, 47 of which met the inclusion criteria. Two additional articles were identified through manual searching of related references lists. See Figure 2-1 for the details of the full search strategy.

Figure 2-1

Search Flow Diagram of Article Inclusion Process.
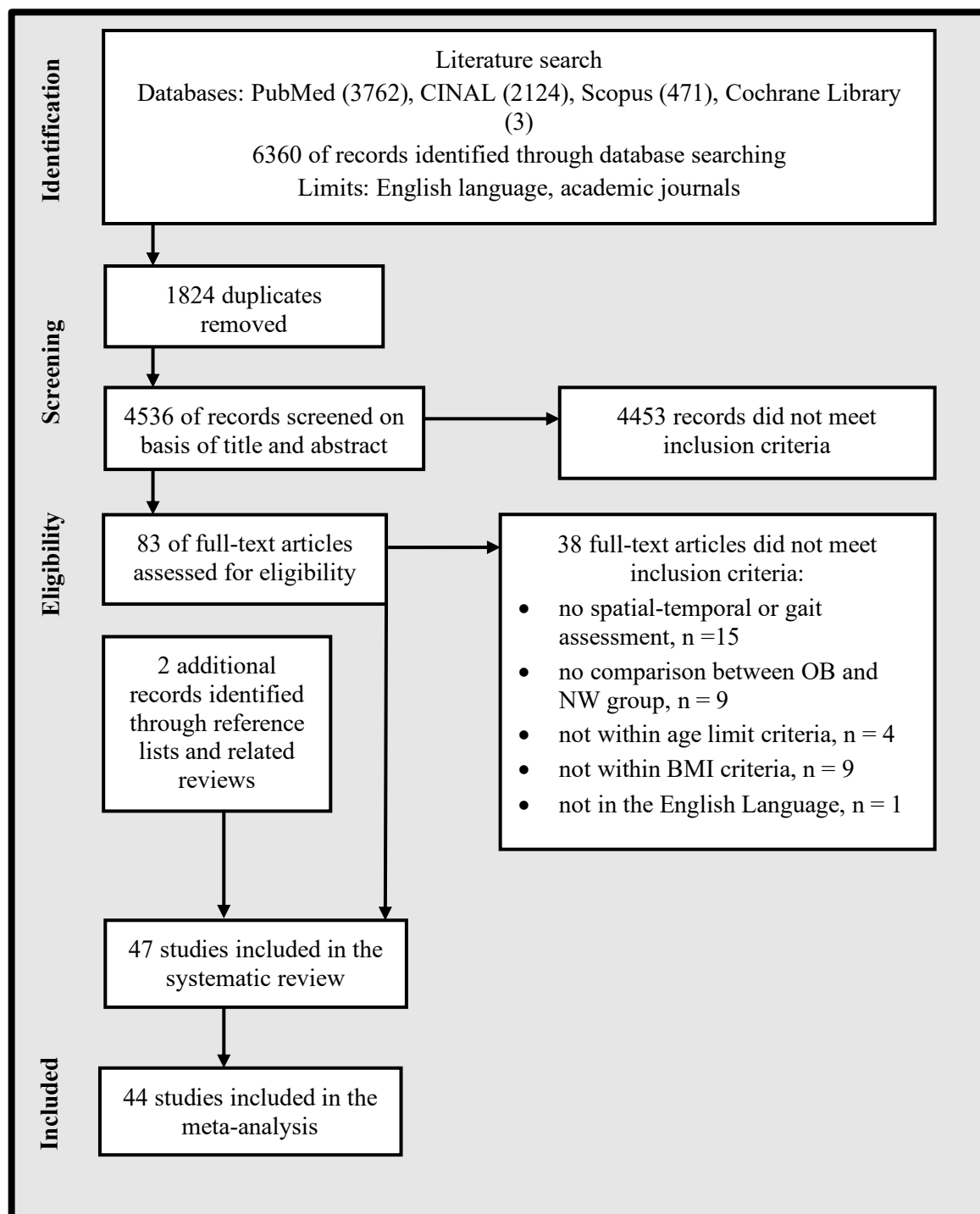
Note: OB obese, NW normal weight, BMI body mass index

Assessment of Methodological Quality

The included studies (Appendix B) had a moderate average quality score of 1.17 $\pm$ 0.14 out of the possible 2.0 points with a range in scores ranging from poor (0.97) to high quality (1.60). The item assessing environmental covariates and confounders were not applicable to any of the included studies. Only five of the 47 included studies reported reliability data for their outcome measures. Similarly, sample size calculations were only reported in 10 of the 47 studies included in the review. Agreement between raters ranged from moderate (0.75) to perfect, with an average Cohen Kappa value across all studies of 0.91 $\pm$ 0.07.

Table 2-1

Risk of Bias

The table below summarizes the full risk-of-bias matrix. Study columns (left to right): Agostini et al. 2017; Altinkaya et al. 2020; Arena et al. 2017; Benedetti et al. 2009; Blaszczyk et al. 2011; Brown et al. 2006; Browning & Kram 2007; Browning et al. 2013; Cimolin et al. 2011; da Silva-Hamu et al. 2013; Deurochers et al. 2021; DeVita & Hortobagyi 2003; Freedman-Silvernail et al.; Garcia et al. 2021; Gill 2019; Hergenroeder et al. 2011; Hills et al. 2006; Jegede et al. 2017; Kim et al. 2021a; Kim et al. 2021b; Koushyar et al. 2020; Koyuncu et al. 2020; Lai et al. 2008; Levine et al. 2008; Lim et al. 2020; Liu & Yang 2017; Maktouf et al. 2020; Malatesta et al. 2009; Menéndez et al. 2019; Menéndez et al. 2020; Meng et al. 2017; Milner et al. 2018; Mondal et al. 2021; Pamukoff et al. 2016a; Pamukoff et al. 2016b; Pau et al. 2021; Retory et al. 2016; Rosso et al. 2019; Russel & Hamill 2011; Russel et al. 2010; Sarkar et al. 2011; Scarpina et al. 2017; Segal et al. 2009; Sheehan & Gormley 2013; Vakula et al. 2019; Vakula et al. 2022; Yocum et al. 2018.

Question	Percentage of Studies Scoring "NA"
Q1. Hypothesis/aim/objective described	76.6%
Q3. Main outcomes described	91.5%
Q4. Study design described	100.0%
Q5. Source of participant population described	36.2%
Q6. Participant eligibility criteria described	83.0%
Q7. Participation rates reported	100.0%
Q8. Characteristics of participants described	100.0%
Q11. Individual covariates an confounders described	44.6%
Q12. Environmental covariates & confounders	0%
Q13. Statistical methods clearly described	76.6%
Q14. Main findings clearly described	100.0%
Q15. Estimates of random variability provided	100.0%
Q16. Estimates of statistical parameters	55.3%
Q17. Sample size calculation performed and reported	21.3%
Q18. Comparison group comparable	72.3%
Q19. Adequate participation rate	100.0%
Q20. Participants recruitment during the same time period	4.3%
Q21. Subject losses accounted for	95.7%
Q29. Observers blinded.	0.0%
Q31. Outcome measures are reliable	10.6%
Q32. Outcome measures are valid	2.1%
Q33. Standard methods of assessment	100.0%
Q34. Observation made during the same time period	6.4%
Q35. History of disease and/or symptoms included in analysis	10.6%
Q36. Adjustment of individual covariates & confounders	36.2%
Q37. Adjustment of environmental covariates & confounders	0.0%
Q40. Outcome reported by level of exposure	10.6%
Q41. Outcome reported by subgroups	14.9%
Q42. Results are applicable to eligible population	100.0%
Q43. Results are applicable to other populations	100.0%

Average Quality Score (0-2): 1.17, 0.97, 1.17, 1.00, 1.37, 1.30, 0.97, 1.13, 1.07, 1.13, 0.97, 1.10, 1.23, 1.37, 1.47, 1.27, 1.27, 1.03, 1.20, 1.07, 1.23, 1.03, 1.10, 1.27, 1.23, 1.13, 1.60, 1.17, 1.03, 1.03, 1.07, 1.20, 1.23, 1.27, 1.13, 1.20, 1.00, 1.00, 1.10, 0.97, 1.07, 1.27, 1.10, 1.23, 1.43, 1.30, 1.13

Cohen Kappa Value: 0.93, 0.82, 0.81, 0.94, 0.85, 0.92, 0.82, 0.87, 0.88, 0.75, 0.94, 0.94, 0.87, 0.93, 0.84, 1.00, 0.88, 0.94, 0.75, 1.00, 0.93, 0.94, 0.88, 0.79, 1.00, 0.94, 1.00, 0.94, 1.00, 0.88, 0.87, 1.00, 0.87, 0.93, 1.00, 0.93, 0.88, 0.83, 0.87, 1.00, 0.87, 0.86, 0.88, 1.00, 1.00, 0.93, 1.00

"Yes" (2) = ■ ; "Partial" (1) = ▨ ; "No" (0) = □ ; "Unable to determine" = UTD ; "Not applicable" = NA

Characteristics of Included Studies

There were 1077 participants with obesity and 922 with normal-weight among the 47 studies included in the systematic review (Table 2-2). The average age of participants with obesity ranged from 21.2 – 51.9 years and 20.4 – 50.0 years for participants with normal-weight in the included studies. Participants consisted solely of females in ten out of the 47 studies, solely of males in three out of the 47 studies, sex was unable to be determined in three studies, and the remaining 31 studies were comprised of both males and females. The average BMI of participants with obesity ranged from 31.0 – 43.5 kg/m^2 and 20.4 – 23.8 kg/m^2 for participants with normal-weight. Twenty-four of the 47 studies included participants with class I obesity, 16 studies included participants with class II obesity, and seven studies included participants with class III obesity. Walking trials were performed overground in 40 studies, on a treadmill in four studies, and a mix of walking surfaces in three studies. Participants in ten studies performed walking trials barefoot, in lab-standardized shoes in nine studies, non-standardized shoes in seven studies, and in 21 studies footwear was unable to be determined. Gait analysis instrumentation ranged from simple (e.g., tape measure and stop watch) to advanced instrumentation (3D motion capture) with the majority of studies utilizing 3D motion capture to measure their outcomes. Finally, at least one outcome measure was normalized to body mass or fat free mass in 20 of the 47 included studies in the systematic review.

In order to reduce sampling bias, Vakula et al. 2022 was included in the meta-analysis, whereas, Garcia et al., 2021 and Vakula et al., 2019 were excluded from the meta-analysis as all three studies reported on similar outcomes. Similarly, Pamukoff

2016a was included but Pamukoff 2016b was excluded from the meta-analyses for

reporting similar outcomes.

Table 2-2-A

Characteristics of Participants and Type of Study

	Sample Size		Age		Sex		BMI, kg/m^2		Type of Study			
Study	OB	NW	OB	NW	OB	NW	OB	NW	Walking Surface	Footwear	Gait analysis instrumentation	Data Normalization
Agostini et al. 2017	10	12	25.6 2.2	26.2 1.5	M 10/F 0	M 12/F 0	31.1 3.3	22.8 1.1	Over-ground	Barefoot	Step 32 ®	ST and DS to %GC
Altinkaya et al. 2020	16	16	22.13 ± 2.42	24.13 ± 2.94	M 8/F 8	M 8/F 8	34.45	21.6	Over-ground	UTD	Timing Sensors	NA
Arena et al. 2017	20	20	23.5 ± 3.2	24.5 ± 3.5	M 11/F 9	M 10/F 10	33.4 ± 3.4	22.3 ± 2.3	Over-ground	Shoes (lab-standardized)	3-D MoCap; Instrumented walkway	NA
Benedetti et al. 2009	26	15	47.5	45	M 10/F 16	M 4/F 11	35.77	21.33	Over-ground	UTD	Inertial measurement units	NA
Błaszczyk et al. 2011	100	36	36.8 ± 12.0	36.2 ± 10.3	M 0/F 100	M 0/F 36	37.1 ± 5.2	21.8 ± 1.7	Over-ground	Shoes	Pressure-sensitive walkway	ST and DS to %GC
Brown et al. 2006	10	10	28.9 ± 7.3	28.7 ± 8.2	M 5/F 5	M 5/F 5	35.6 ± 4.9	22.1 ± 1.6	Treadmill (DB)	Shoes (personal)	Tape measure and stop watch	ST and DS to %GC
Browning & Kram 2007	32	19	28.5 ± 7.6	22.8 ± 3.6	M 14/F 18	M 9/F 10	33.9 ± 3.6	21.6 ± 2.0	Treadmill (DB)	Shoes	3-D MoCap; Instrumented treadmill	ST and DS to %GC
Browning et al. 2013	19	20	25.5 ± 6.9	23.6 ± 5.0	M 10/F 9	M 10/F 10	33.6 ± 2.7	21.35 ± 2.2	Over-ground	UTD	Tape measure and stop watch	NA
Cimolin et al. 2011	10	10	33.6 ± 5.2	33.4 ± 9.6	M 0/F 10	M 0/F 10	39.26 ± 2.39	22.8 ± 3.2	Over-ground	Barefoot	3-D MoCap; Instrumented walkway	ST and DS to %GC; WS and SL to PH
da Silva-Hamu et al. 2013	24	24	35.20 ± 9.9	36.33 ± 11.14	M 0/F 24	M 0/F 24	31.85 ± 2.94	21.82 ± 1.58	Over-ground	UTD	3-D MoCap; Instrumented walkway	NA
Desrochers et al. 2021	14	20	50.36 ± 10.97	45.55 ± 8.77	M 2/F 12	M 6/F 14	40.95 ± 5.46	23.77 ± 2.53	Over-ground	UTD	Pressure-sensitive walkway	ST and DS to %GC
DeVita & Hortobagyi 2003	21	18	39.5 ± 8.8	20.8 ± 2.4	M 8/F 13	M 7/F 11	42.3 ± 7.7	22.7 ±2.9	Over-ground	Shoes	Instrumented walkway; Timing sensors	ST to %GC
Fernández Menéndez et al. 2019	30	50	35.4 ± 4.1	31.8 ± 4.5	M 4/F 9	M 5/F 8	38.6 ± 3.5	21.4 ± 2.2	Treadmill (SB)	UTD	Instrumented treadmill	NA
Fernández Menéndez et al. 2020	30	19	29.5 ± 1.3	31.2 ± 1.2	M 14/F 16	M 10/F 9	39.6 ± 0.6	21.4 ± 0.5	Treadmill (SB)	UTD	Instrumented treadmill	NA
Freedman-Silvernail et al. 2013	13	13	32.7 ± 7.9	29.0 ± 5.8	M 4/F 9	M 5/F 8	33.8 ± 2.5	21.9 ± 1.5	Over-ground	Shoes (lab-standardized)	Timing sensors	NA
Garcia et al. 2021	11	13	39.9 ± 7.9	29.6 ± 5.7	M 2/F 9	M 5/F 8	43.0 ± 4.2	22.0 ± 1.5	Over-ground	Shoes (lab-standardized)	3-D MoCap; Instrumented walkway	NA
Gill 2019	10	10	23.8 ± 5.6	23.0 ± 4.1	M 5/F 5	M 5/F 5	34.4 ± 3.9	22.4 ± 2.1	Over-ground	UTD	Pressure-sensitive walkway	ST to %GC
Hergenroeder et al. 2011	48	48	21.9 ± 2.6	22.9 ± 3.57	M 24/F 24	M 24/F 24	33.03 ± 0.59	21.59 ± 0.25	Over-ground	UTD	Tape measure and stop watch	NA
Hills et al. 2006	36	13	42.03 ± 9.30	38.20 ± 7.04	M 0/F 36	M 0/F 13	41.41 ± 4.63	22.56 ± 1.61	Over-ground	UTD	Tape measure and stop watch	NA
Jegede et al. 2017	30	10	51.9 ± 2.8	50.0 ± 1.8	M 0/F 30	M 0/F 10	38.02 ± 5.0	22.7 ± 0.5	Over-ground	Barefoot	Footprint method	NA
Kim et al. 2021a	30	20	47.8 ± 10.8	36.9 ± 12.4	UTD	UTD	35.5 ± 6.7	24.8 ± 3.0	Over-ground; treadmill (DB)	UTD	Pressure-sensitive walkway; 3-D MoCap	NA
Kim et al. 2021b	30	28	32.0 ± 8.26	29.32 ± 6.06	M 7/F 12	M 9/F 10	35.03 ± 4.91	23.55 ± 1.17	Over-ground	Barefoot	Pressure-sensitive walkway	NA
Koushyar et al. 2020	26	21	28.51 ± 3.86	27.10 ± 5.44	M 0/F 26	M 0/F 21	39.39 ± 7.78	22.65 ± 2.52	Over-ground	Shoes (lab-standardized)	3-D MoCap; Instrumented walkway	NA
Koyuncu et al. 2020	19	19	28.27 ± 4.03	23.21 ± 5.46	M 7/F 12	M 9/F 10	42.62 ± 8.01	22.37 ± 2.49	Over-ground; Treadmill	Shoes	3-D MoCap	NA
Lai et al. 2008	10	10	23.1 ± 3.8	21.7 ± 3.3	M 0/F 10	M 0/F 10	33.7 ± 2.9	22.5 ± 1.8	Over-ground	Barefoot	3-D MoCap; Instrumented walkway	SL to PH; ST and DS to %GC
Levine et al. 2008	13	14	23.38 ± 3.12	23.29 ± 3.63	M 13/F 0	M 14/F 0	34.08 ± 3.69	21.83 ± 2.14	Over-ground	UTD	Inertial measurement units	NA

OB obese, NW normal weight, WS walking speed, SL step length, SW step width, ST stance time, DS double support time, PH participant height, %GC percentage of gait cycle, SB single belt, DB dual belt, NA not avaliable, UTD unable to determine

Table 2-2-B

Characteristics of Participants and Type of Study Continued

	Sample Size		Age		Sex		BMI, kg/m²		Type of Study			
Study	OB	NW	OB	NW	OB	NW	OB	NW	Walking Surface	Footwear	Gait analysis instrumentation	Data Normalization
Lim et al. 2020	14	14	35.36 ± 8.67	27.57 ± 8.62	M 6/F 8	M 6/F 8	33.06 ± 4.29	21.33 ± 1.53	Over-ground	Shoes	Inertial measurement units	ST and DS to %GC
Liu & Yang 2017	12	10	37.8 ± 6.0	38.4 ± 9.9	M 5/F 12	M 5/F 5	33.7 ± 2.5	22.4 ± 2.0	Over-ground	UTD	3-D MoCap	WS to PH; DS to %GC
Maktouf et al. 2020	16	16	27.3 ± 1.5	26.6 ±1.0	M 10/F 6	M 8/F 8	34.4 ±0.8	22.7 ±0.5	Over-ground; treadmill (SB)	UTD	Instrumented treadmill	ST and DS to %GC
Malatesta et al. 2009	23	21	24.9 ± 5.7	23.5 ± 4.0	M 15/F 8	M 7/F 14	35.1 ± 3.9	21.7 ± 2.4	Over-ground	UTD	3-D MoCap	ST and DS to %GC
Meng et al. 2017	10	10	23.8 ± 6.6	24.4 ± 2.3	M 5/F 5	M 5/F 5	35.3 ± 3.1	21.9 ± 1.2	Over-ground	Shoes (personal)	Pressure-sensitive walkway	WS and SL to PH; ST and DS to %GC
Milner et al. 2018	10	10	26.6 ± 5.8	26.5 ± 4.5	M 5/F 5	M 5/F 5	33.7 ± 3.8	22.2 ± 1.6	Over-ground	Shoes (lab-standardized)	3-D MoCap; Timing Sensors	NA
Mondal et al. 2021	30	30	32.2 ± 6.0	28.2 ± 3.9	M 15/F 15	M 15/F 15	33.9 ± 3.7	22.8 ± 1.8	Over-ground	Barefoot	Footprint method	NA
Pamukoff et al. 2016a	15	15	21.2 ± 1.2	20.4 ± 1.4	M 7/F 8	M 7/F 8	33.5 ± 6.42	20.4 ± 1.38	Over-ground	Barefoot	Timing sensors	NA
Pamukoff et al. 2016b	15	15	21.2 ± 1.2	20.4 ± 1.4	UTD	UTD	33.5 ± 6.42	20.4 ± 1.38	Over-ground	UTD	Timing sensors	NA
Pau et al. 2021	26	26	28.7 ± 7.6	28.5 ± 7.8	M 11/F 15	M 11/F 15	40.4 ± 0.8	21.8 ± 2.8	Over-ground	UTD	3-D MoCap; Instrumented walkway	ST and DS to %GC
Retory et al. 2016	15	10	42.0 ± 11.9	35.4 ± 13.8	M 4/F 11	M 2/F 8	43.5 ± 5.2	22.8 ± 1.4	Over-ground	UTD	Tape measure and stop watch	NA
Rosso et al. 2019	10	12	26 ± 2.2	26 ± 1.5	M 10/F 0	M 12/F 0	31.1 ± 3.3	22.7 ± 1.2	Over-ground	Barefoot	Inertial measurement units	ST to %GC
Russel & Hamill 2011	10	10	25.3 ± 9.8	25.1 ± 3.8	M 0/F 10	M 0/F 10	33.09 ± 4.22	22.66 ± 0.86	Over-ground	UTD	3-D MoCap and timing gates	NA
Russel et al. 2010	14	14	29.3 ± 10.4	26.1 ± 6.9	M 0/F 14	M 0/F 14	37.2 ± 6.1	22.4 ± 1.2	Over-ground	Shoes (lab-standardized)	Timing sensors	NA
Sarkar et al. 2011	30	30	26.05 ± 0.93	26.95 ± 0.89	M 15/F 15	M 15/F 15	35.38 ± 0.26	21.95 ± 1.10	Over-ground	Barefoot (socks)	Footprint method	NA
Scarpina et al. 2017	18	18	36 ± 8	35 ± 9	M 0/F 18	M 0/F 18	39.67 ± 4.72	20.59 ± 1.81	Over-ground	UTD	3-D MoCap	SL to PH
Segal et al. 2009	40	19	49.2 ± 5.1	48.7 ± 3.8	M 33/F 7	M 17/F 2	35.6 ± 4.7	22.8 ± 1.8	Over-ground	UTD	3-D MoCap	NA
Sheehan & Gormley 2013	25	25	39.2 ± 16.5	39.8 ± 16.8	M 15/F 10	M 15/F 10	31.0 ± 4.1	23.4 ± 2.3	Over-ground	Barefoot	3-D MoCap; Instrumented walkway	ST to %GC
Vakula et al. 2019	48	48	22.8 ± 3.5	22.0 ± 2.6	M 24/F 24	M 24/F 24	33.1 ± 4.1	21.6 ± 1.71	Over-ground	Shoes (lab-standardized)	3-D MoCap; Instrumented walkway	SL and SW to PH
Vakula et al. 2022	48	47	21.90 ± 3.16	22.90 ± 3.13	M 24/F 24	M 24/F 24	33.03 ± 3.20	21.60 ± 3.16	Over-ground	Shoes (lab-standardized)	3-D MoCap; Instrumented walkway	SL and SW to PH
Yocum et al. 2018	10	14	25.7 ± 5.8	21.6 ± 0.5	UTD	UTD	32.8 ± 2.7	22.5 ± 1.9	Over-ground	Shoes (lab-standardized)	3-D MoCap; Instrumented walkway	NA

OB obese, *NW* normal weight, *WS* walking speed, *SL* step length, *SW* step width, *ST* stance time, *DS* double support time, *PH* participant height, *%GC* percentage of gait cycle, *SB* single belt, *DB* dual belt, *NA* not avaliable, *UTD* unable to determine

Additional Analysis

Self-selected walking speed was calculated from the distance covered in 6-minutes in one study (Retory et al., 2016). Cadence was calculated from step time in the one study as steps per minute (Scarpina et al., 2017). Self-selected walking speed (Arena et al., 2017; Hills et al., 2006), stance and double support period (Blaszczyk et al., 2011), and step width (Browning & Kram, 2007) were digitized from graphs in four studies.

The following subgroups were combined into a single group for analysis using the Cochrane formula (J. Higgins et al., 2021):

- Normal arch and low arch groups (D. Kim et al., 2021).

- Class II and Class III obesity groups (Gill, 2019).

- Class I, II, III obesity groups (Blaszczyk et al., 2011; Hergenroeder et al., 2011).

- Male and female groups (Arena et al., 2017; Browning et al., 2006; Garcia et al., 2021).

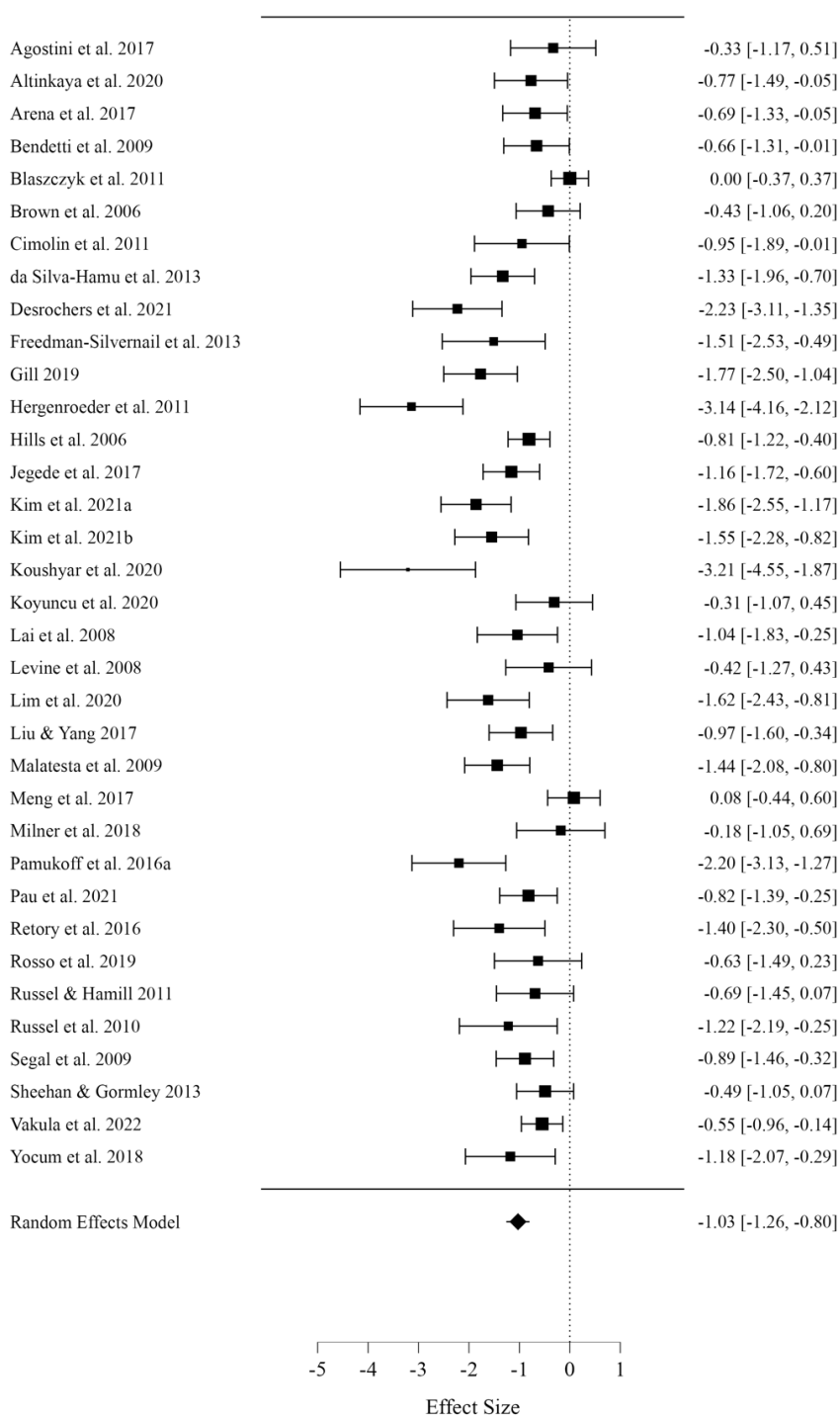- Centrally obese and lower-body obese (i.e., distribution of adipose tissue) groups (Segal et al., 2009).

A single study-wise effect size was calculated using a fixed-effects model in the following studies to combine:

- Left and right outcome measures (da Silva-Hamu et al., 2013; Meng et al., 2017).

- Standardized walking speeds (Browning & Kram, 2007; Fernández Menéndez et al., 2019, 2020).

- Walking trials 1 and 2 (Hills et al., 2006).

Self-selected Spatiotemporal Gait Measures

Obesity significantly decreased self-selected walking speed with a pooled effect size of -1.03 (95% CI: -1.26, -0.80; $P = <0.001$; $I^2 = 74\%$) for the 35 studies included in the analysis (Figure 2-2). The funnel plot was asymmetrical and the Egger test for publication bias was significant ($P = <0.001$). By subgroup class I obesity included 17 studies and had an overall significant effect size of -0.95 (95% CI: -1.24, -0.66; P =

<0.001; I^2 = 60%), class II obesity included 13 studies and had an overall significant effect size of -0.93 (95% CI: -1.35, -0.52; P = <0.001; I^2 = 84%), and class III obesity included five studies with an overall significant effect size of -1.50 (95% CI: -1.98, -1.02; P = <0.001; I^2 = 52%).

Figure 2-2

Forest Plot of Self-Selected Walking Speed

Agostini et al. 2017	-0.33 [-1.17, 0.51]
Altinkaya et al. 2020	-0.77 [-1.49, -0.05]
Arena et al. 2017	-0.69 [-1.33, -0.05]
Bendetti et al. 2009	-0.66 [-1.31, -0.01]
Blaszczyk et al. 2011	0.00 [-0.37, 0.37]
Brown et al. 2006	-0.43 [-1.06, 0.20]
Cimolin et al. 2011	-0.95 [-1.89, -0.01]
da Silva-Hamu et al. 2013	-1.33 [-1.96, -0.70]
Desrochers et al. 2021	-2.23 [-3.11, -1.35]
Freedman-Silvernail et al. 2013	-1.51 [-2.53, -0.49]
Gill 2019	-1.77 [-2.50, -1.04]
Hergenroeder et al. 2011	-3.14 [-4.16, -2.12]
Hills et al. 2006	-0.81 [-1.22, -0.40]
Jegede et al. 2017	-1.16 [-1.72, -0.60]
Kim et al. 2021a	-1.86 [-2.55, -1.17]
Kim et al. 2021b	-1.55 [-2.28, -0.82]
Koushyar et al. 2020	-3.21 [-4.55, -1.87]
Koyuncu et al. 2020	-0.31 [-1.07, 0.45]
Lai et al. 2008	-1.04 [-1.83, -0.25]
Levine et al. 2008	-0.42 [-1.27, 0.43]
Lim et al. 2020	-1.62 [-2.43, -0.81]
Liu & Yang 2017	-0.97 [-1.60, -0.34]
Malatesta et al. 2009	-1.44 [-2.08, -0.80]
Meng et al. 2017	0.08 [-0.44, 0.60]
Milner et al. 2018	-0.18 [-1.05, 0.69]
Pamukoff et al. 2016a	-2.20 [-3.13, -1.27]
Pau et al. 2021	-0.82 [-1.39, -0.25]
Retory et al. 2016	-1.40 [-2.30, -0.50]
Rosso et al. 2019	-0.63 [-1.49, 0.23]
Russel & Hamill 2011	-0.69 [-1.45, 0.07]
Russel et al. 2010	-1.22 [-2.19, -0.25]
Segal et al. 2009	-0.89 [-1.46, -0.32]
Sheehan & Gormley 2013	-0.49 [-1.05, 0.07]
Vakula et al. 2022	-0.55 [-0.96, -0.14]
Yocum et al. 2018	-1.18 [-2.07, -0.29]
Random Effects Model	-1.03 [-1.26, -0.80]

Effect Size

Obesity significantly decreased step length at self-selected walking speed with a pooled effect size of -0.95 (95% CI: -1.22, -0.68; P = <0.001; I^2 = 73%) for the 21 studies included in the analysis (Figure 2-3). The funnel plot was asymmetrical and the Egger test for publication bias was significant (P = 0.003). By subgroup class I obesity included ten studies and had an overall significant effect size of -0.99 (95% CI: -1.32, -0.66; P = <0.001; I^2 = 58%), class II obesity included nine studies and with a significant effect size of -0.76 (95% CI: -1.21, -0.31; P = <0.001; I^2 = 79%), and class III obesity included two studies with a significant effect size of -1.69 (95% CI: -2.47, -0.90; P = <0.001; I^2 = 55%).

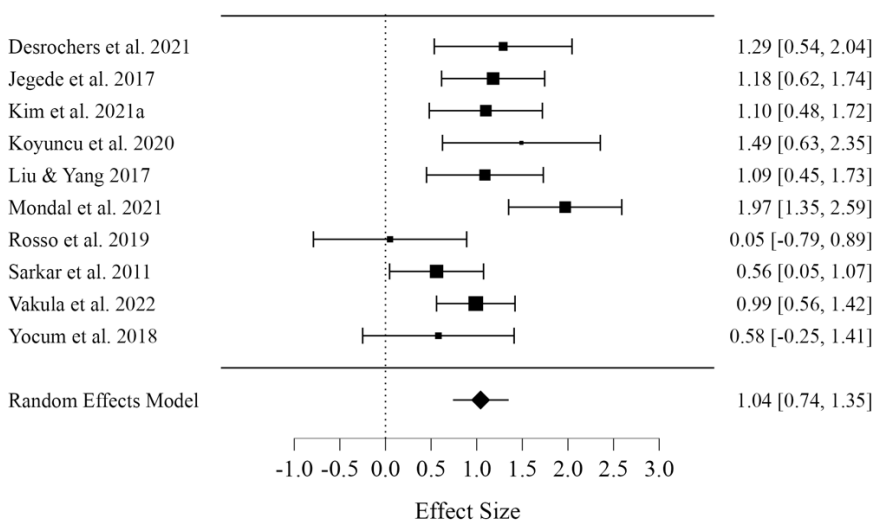**Figure 2-3**

Forest Plot of Step Length at Self-Selected Walking Speed

Bendetti et al. 2009	-0.23 [-0.86, 0.40]
Blaszczyk et al. 2011	-0.08 [-0.46, 0.30]
Cimolin et al. 2011	-3.10 [-4.48, -1.72]
da Silva-Hamu et al. 2013	-1.19 [-1.63, -0.75]
Desrochers et al. 2021	-2.15 [-3.02, -1.28]
Jegede et al. 2017	-1.09 [-1.64, -0.54]
Kim et al. 2021a	-1.32 [-1.96, -0.68]
Koushyar et al. 2020	-0.96 [-1.89, -0.03]
Lai et al. 2008	-1.14 [-1.95, -0.33]
Lim et al. 2020	-1.95 [-2.81, -1.09]
Liu & Yang 2017	-0.90 [-1.52, -0.28]
Malatesta et al. 2009	-0.53 [-1.11, 0.05]
Meng et al. 2017	0.00 [-0.62, 0.62]
Milner et al. 2018	-0.16 [-1.04, 0.72]
Mondal et al. 2021	-1.41 [-1.98, -0.84]
Pau et al. 2021	-1.34 [-1.96, -0.72]
Rosso et al. 2019	-1.20 [-2.12, -0.28]
Russel et al. 2010	-0.80 [-1.72, 0.12]
Scarpina et al. 2017	-0.77 [-1.45, -0.09]
Sheehan & Gormley 2013	-0.98 [-1.57, -0.39]
Vakula et al. 2022	-0.28 [-0.68, 0.12]
Random Effects Model	-0.95 [-1.22, -0.68]

Effect Size

Obesity significantly increases step width at self-selected walking speed with a pooled effect size of 1.04 (95% CI: 0.74, 1.35; P = <0.001 I^2 = 57%) for the 10 studies included in the analysis (Figure 2-4). The funnel plot was symmetrical and the Egger test for publication bias was not significant (P = 0.756). By subgroup class I obesity included five studies and had an overall significant effect size of 1.04 (95% CI: 0.40, 1.69; P =

0.002; I^2 = 77%), class II obesity included four studies and had an overall significant effect size of 0.95 (95% CI: 0.64, 1.27; P = <0.001; I^2 = 17%), and the class III obesity subgroup included one study (Desrochers et al., 2021) and thus, no meta-analysis was performed.

Figure 2-4

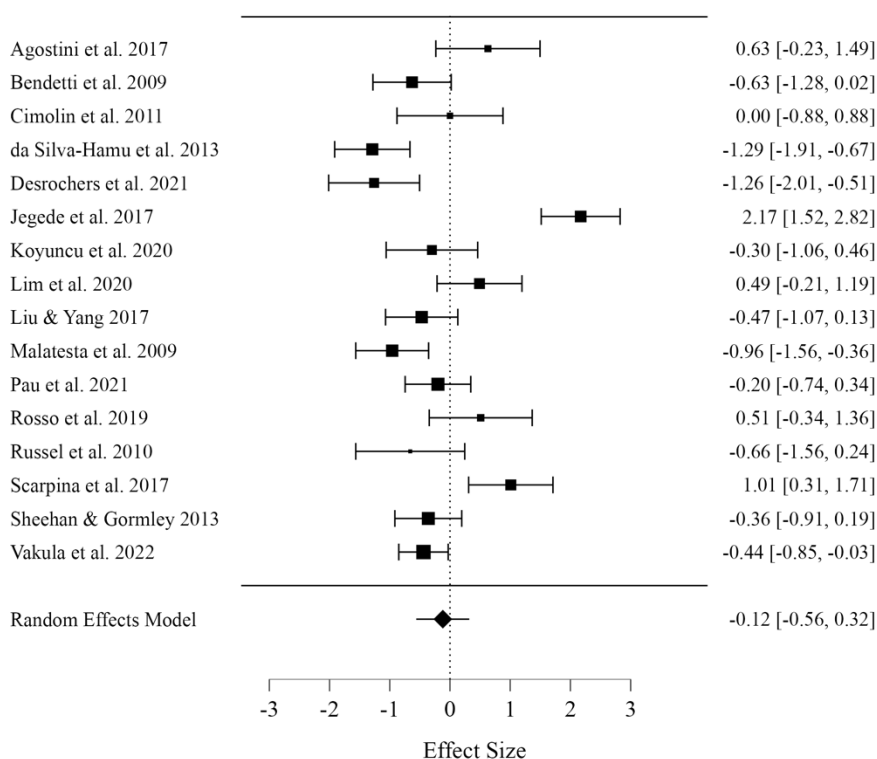*Forest Plot of Step Width at Self-Selected Walking Speed*

Obesity had a nonsignificant effect on cadence at self-selected walking speed with a pooled effect size of -0.12 (95% CI: -0.56, 0.32; P = 0.599; I^2 = 86%) for the 16 studies included in the analysis (Figure 2-5). The funnel plot was symmetrical and the Egger test for publication bias was not significant (P = 0.491). By subgroup class I obesity included eight studies and had an overall nonsignificant effect size of -0.21 (95% CI: -0.67, 0.24; P = 0.364; I^2 = 73%), class II obesity included six studies with a nonsignificant effect size of 0.18 (95% CI: -0.78, 1.14; P = 0.708; I^2 = 92%), and class III

obesity included two studies with a nonsignificant effect size of -0.70 (95% CI: -1.73,

0.34; P = 0.188; I^2 = 80%).

Figure 2-5

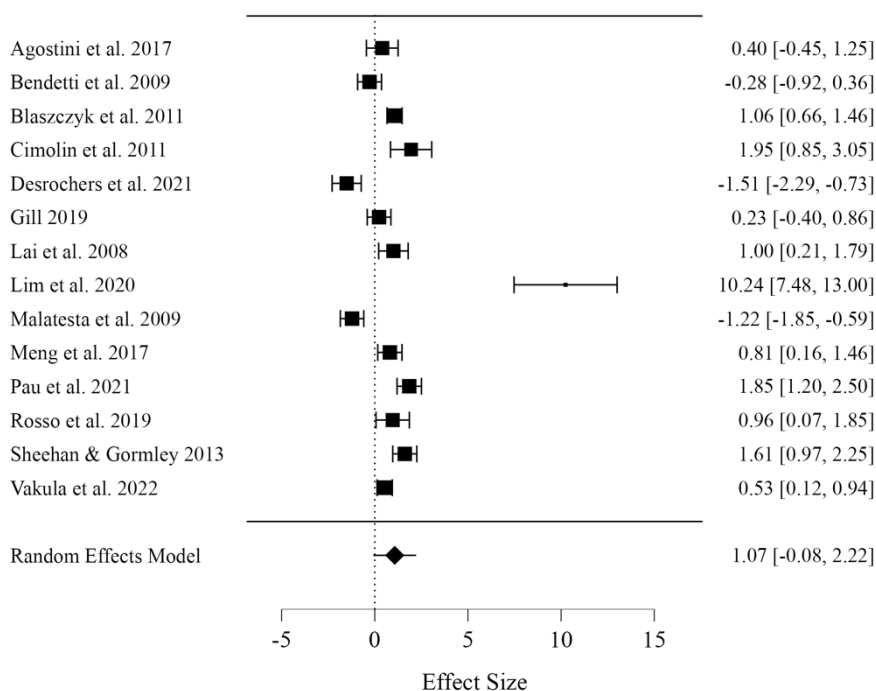*Forest Plot of Cadence at Self-Selected Walking Speed*

Agostini et al. 2017	0.63 [-0.23, 1.49]
Bendetti et al. 2009	-0.63 [-1.28, 0.02]
Cimolin et al. 2011	0.00 [-0.88, 0.88]
da Silva-Hamu et al. 2013	-1.29 [-1.91, -0.67]
Desrochers et al. 2021	-1.26 [-2.01, -0.51]
Jegede et al. 2017	2.17 [1.52, 2.82]
Koyuncu et al. 2020	-0.30 [-1.06, 0.46]
Lim et al. 2020	0.49 [-0.21, 1.19]
Liu & Yang 2017	-0.47 [-1.07, 0.13]
Malatesta et al. 2009	-0.96 [-1.56, -0.36]
Pau et al. 2021	-0.20 [-0.74, 0.34]
Rosso et al. 2019	0.51 [-0.34, 1.36]
Russel et al. 2010	-0.66 [-1.56, 0.24]
Scarpina et al. 2017	1.01 [0.31, 1.71]
Sheehan & Gormley 2013	-0.36 [-0.91, 0.19]
Vakula et al. 2022	-0.44 [-0.85, -0.03]
Random Effects Model	-0.12 [-0.56, 0.32]

Obesity had a no effect on stance period at self-selected walking speed with a

pooled effect size of 1.07 (95% CI: -0.08, 2.22; P = 0.068; I^2 = 98%) for the 14 studies

included in the analysis (Figure 2-6). The funnel plot was asymmetrical and the Egger

test for publication bias was significant (P = <0.001). By subgroup class I obesity

included six studies and had an overall nonsignificant effect size of 2.28 (95% CI: -0.51,

5.06; $P = 0.109$; $I^2 = 99\%$), class II obesity included five studies with a nonsignificant

effect of 0.43 (95% CI: -0.62, 1.48; $P = 0.424$; $I^2 = 93\%$), and class III obesity included

three studies with a nonsignificant effect of 0.20 (95% CI: -1.69, 2.09; $P = 0.837$; $I^2 =$

96%).

Figure 2-6

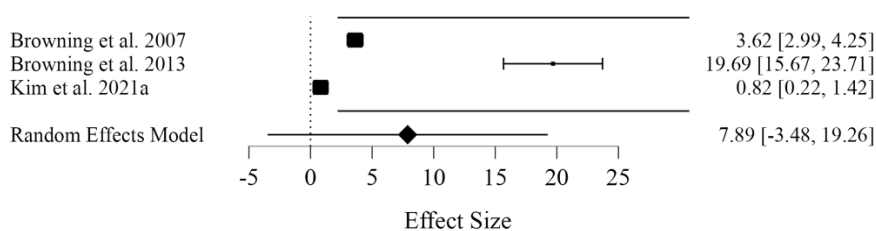*Forest Plot of Stance Period at Self-Selected Walking Speed*

Agostini et al. 2017	0.40 [-0.45, 1.25]
Bendetti et al. 2009	-0.28 [-0.92, 0.36]
Blaszczyk et al. 2011	1.06 [0.66, 1.46]
Cimolin et al. 2011	1.95 [0.85, 3.05]
Desrochers et al. 2021	-1.51 [-2.29, -0.73]
Gill 2019	0.23 [-0.40, 0.86]
Lai et al. 2008	1.00 [0.21, 1.79]
Lim et al. 2020	10.24 [7.48, 13.00]
Malatesta et al. 2009	-1.22 [-1.85, -0.59]
Meng et al. 2017	0.81 [0.16, 1.46]
Pau et al. 2021	1.85 [1.20, 2.50]
Rosso et al. 2019	0.96 [0.07, 1.85]
Sheehan & Gormley 2013	1.61 [0.97, 2.25]
Vakula et al. 2022	0.53 [0.12, 0.94]
Random Effects Model	1.07 [-0.08, 2.22]

Effect Size

Obesity significantly increases the double support period at self-selected walking

speed with a pooled effect size of 1.86 (95% CI: 0.64, 3.09; $P = 0.003$; $I^2 = 98\%$) for the

13 studies included in the analysis (Figure 2-7). The funnel plot was asymmetrical and

the Egger test for publication bias was significant ($P = <0.001$). By subgroup class I

obesity included four studies and had an overall nonsignificant effect size of 2.60 (95% CI: -0.93, 6.12; P = 0.149; I^2 = 99%), class II obesity included seven studies with a significant effect of 0.94 (95% CI: 0.62, 1.25; P = <0.001; I^2 = 46%), and class III obesity included two studies with a nonsignificant effect of 4.26 (95% CI: -0.57, 9.09; P = 0.084; I^2 = 97%).

Figure 2-7

Forest Plot of Double Support Period at Self-Selected Walking Speed
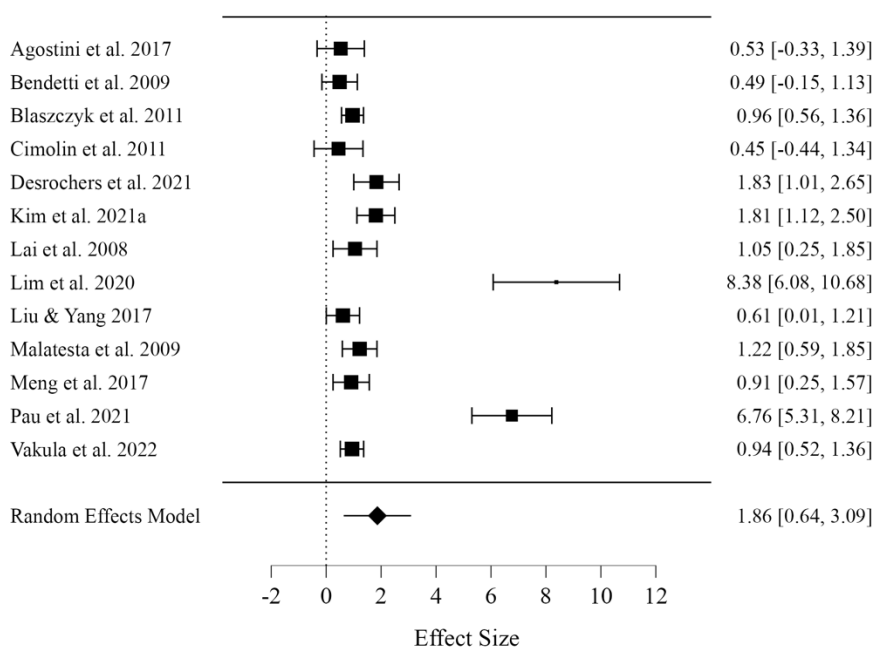
**Standardized Spatiotemporal Gait Measures**

Obesity had a nonsignificant effect on step length at standardized walking speed with a pooled effect size of -0.07 (95% CI: -0.29, 0.15; P = 0.535; I^2 = 30%) for the four

studies included in the analysis (Figure 2-8). The funnel plot was symmetrical and the

Egger test for publication bias was nonsignificant (P = 0.134). By subgroup class II

obesity included two studies and had an overall nonsignificant effect size of -0.19 (95%

CI: -0.72, 0.35; P = 0.495; I^2 = 73%), and the class I and III obesity subgroups included

one study each and thus, no meta-analysis was performed.

Figure 2-8

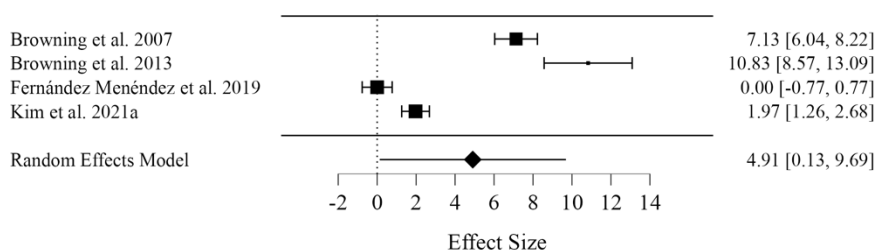*Forest Plot of Step Length at Standardized Walking Speed*
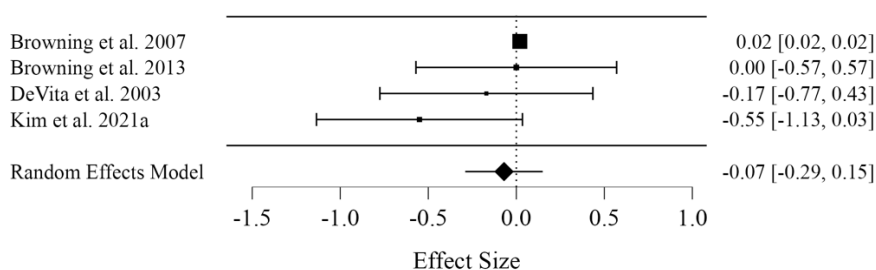
Obesity had a nonsignificant effect on step width at standardized walking speed

with a pooled effect size of 7.81 (95% CI: -1.41, 17.03; P = 0.097; I^2 => 99%) for the

three studies included in the analysis (Figure 2-9). The funnel plot was symmetrical and

the Egger test for publication bias was nonsignificant (P = 0.134). By subgroup class II

obesity included two studies and had an overall nonsignificant effect size of -0.19 (95%

CI: -0.72, 0.35; P = 0.495; I^2 = 73%), the class I obesity subgroup included one study,

and the class III subgroup contained no studies, and thus, no meta-analysis was

performed.

Figure 2-9

Forest Plot of Step Width at Standardized Walking Speed

Browning et al. 2007	3.62 [2.99, 4.25]
Browning et al. 2013	19.69 [15.67, 23.71]
Kim et al. 2021a	0.82 [0.22, 1.42]
Random Effects Model	7.89 [-3.48, 19.26]

Obesity had a nonsignificant effect on cadence at standardized walking speed with a pooled effect size of -0.25 (95% CI: -0.67, 0.17; $P = 0.248$; $I^2 = 50\%$) for the three studies included in the analysis (Figure 2-10). The funnel plot was asymmetrical and the Egger test for publication bias was significant ($P = 0.051$). Each subgroup contained one study each and thus, no meta-analysis was performed.

Figure 2-10

Forest Plot of Cadence at Standardized Walking Speed

Browning et al. 2007	-0.58 [-0.96, -0.20]
Browning et al. 2013	0.00 [-0.57, 0.57]
DeVita et al. 2003	0.00 [-0.63, 0.63]
Random Effects Model	-0.25 [-0.67, 0.17]
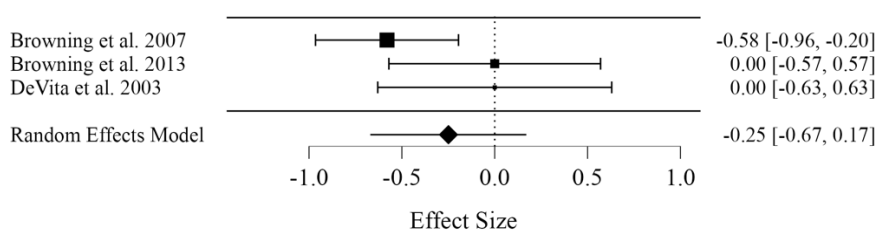
Obesity had a nonsignificant effect on stance period at standardized walking speed with a pooled effect size of 3.80 (95% CI: -1.46, 9.06; P = 0.157; I^2 = > 99%) for the four studies included in the analysis (Figure 2-11). The funnel plot was asymmetrical and the Egger test for publication bias was significant (P = 0.022). By subgroup class I obesity included two studies and had an overall nonsignificant effect size of 5.71 (95% CI: -6.16, 17.57; P = 0.346; I^2 = 99%), and the class II and III obesity subgroups included one study each and thus, no meta-analysis was performed.

Figure 2-11

Forest Plot of Stance Period at Standardized Walking Speed
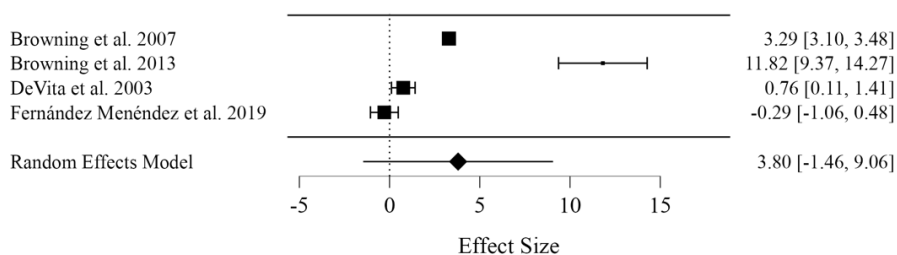
Obesity significantly increases the double support period at standardized walking speed with a pooled effect size of 4.91 (95% CI: 0.13, 9.69; P = 0.044; I^2 = 99%) for the four studies included in the analysis (Figure 2-12). The funnel plot was asymmetrical and the Egger test for publication bias was significant (P = 0.005). By subgroup class I obesity included two studies and had an overall nonsignificant effect size of 5.36 (95% CI: -5.25, 15.97; P = 0.322; I^2 = 99%), class II obesity included two studies and had an overall nonsignificant effect size of 4.53 (95% CI: -0.52, 9.59; P = 0.079; I^2 = 98%), and

the class III obesity subgroup included no studies and thus, no meta-analysis was performed.

Figure 2-12

Forest Plot of Double Support Period at Standardized Walking Speed

Browning et al. 2007		7.13 [6.04, 8.22]
Browning et al. 2013		10.83 [8.57, 13.09]
Fernández Menéndez et al. 2019		0.00 [-0.77, 0.77]
Kim et al. 2021a		1.97 [1.26, 2.68]
Random Effects Model		4.91 [0.13, 9.69]

Effect Size

Discussion

The objective of this systematic review and meta-analysis was to evaluate the effect of obesity on spatiotemporal gait parameters (self-selected walking speed, step length, step width, cadence, and stance and double support period). We compared these gait parameters at self-selected and standardized gait speeds in adults 18-55 years old with or without obesity. In total there were 47 studies included in the systematic review and 44 included in the meta-analysis. To our best knowledge, this is the first study attempting to increase the clarity surrounding the effect of obesity on spatiotemporal measures of gait by performing a systematic review and meta-analysis. The results from this report, in general, provide evidence that obesity alters spatiotemporal measures of gait. Specifically, obesity reduces self-selected walking speed and step length, but increases step width at self-selected walking speed and the double-support period

at self-selected and standardized walking speeds. Notably, the effects of obesity on spatiotemporal measures of gait varied by level of obesity (i.e., class I, II, or III). A decreased self-selected walking speed with obesity was reported in all but one of the 44 studies included in the meta-analysis. On average, individuals with obesity walked approximately 9.4% slower than normal weight individuals at self-selected walking speed (1.22 m/s vs 1.34 m/s). The decreased self-selected walking speed with obesity is an important finding considering reduced walking speed contributes to mobility disability, falls, and mortality in older adults (Abellan Van Kan et al., 2009; Doi et al., 2020; Studenski et al., 2011). Our result is consistent with a previous systematic review about the effects of obesity on lower-extremity biomechanics which reported a reduced walking speed in six studies on individuals with obesity (Runhaar et al., 2011). A reduced walking speed may be an attempt by individuals with obesity to minimize metabolic cost, reduce ground reaction forces, and reduce muscular forces needed to maintain speed and postural stability while walking (Browning et al., 2006; Browning & Kram, 2007; DeVita & Hortobágyi, 2003; Vakula et al., 2022).

Walking speed is highly influential on spatiotemporal measures of gait. For instance, as walking speed is reduced, step length is decreased, and stance and double support periods are elongated (Browning & Kram, 2007; Fukuchi et al., 2019). Therefore, our findings on step length, step width, and double support period at self-selected walking speed must be interpreted with caution as they are likely influenced in part by the reduced walking speed with obesity. However, similar to previous results by Browning & Kram (2007), our results extend the evidence that suggests regardless of walking speed, adults with obesity elongate their double support period. The double support period is the most stable phase of the gait cycle, as it is the period in which the bodies mass is distributed between the lower-extremity (Whittle, 2014; Winter, 1995).

Furthermore, our results indicate that individuals with obesity take wider steps at self-selected speed, which would increase stability in the frontal plane. Together, these adaptations during the gait cycle may be a strategy utilized by individuals with obesity to increase dynamic stability while walking, which may be compromised by lower-extremity muscle dysfunction among other factors (Giuliani et al., 2020; Vakula et al., 2022).

At self-selected speeds, step length was significantly reduced but cadence was not affected with obesity. As a reduction in walking speed is a product of shorter and/or fewer steps, our results imply that individuals with obesity may reduce their step length rather than cadence in order to reduce their self-selected walking speed. Furthermore, taking shorter steps has been shown to reduce the loads placed on the knee joint during walking (Milner et al., 2018), and thus, may be a strategy to limit overloading the knee joint. This notion is further supported by our subgroup analysis which shows the reduction in step length with obesity is larger in individuals with class III obesity.

Surprisingly, we found no overall effect of obesity on stance period. While an elongated stance period may be an attempt to improve dynamic stability during gait by increasing the amount of time spent in contact with the ground (Hills et al., 2002), our results imply that at self-selected and standardized walking speeds, the stance period did not differ between individuals with normal weight or obesity at any classification level. The 14 studies included in our analysis did near significance, possibly suggesting that stance period is elongated with obesity. However, only nine of the 14 included studies supported an increased effect of obesity on stance time at self-selected gait speed. Alternatively, two of the 14 included studies noted a shorter stance time among

individuals with obesity, which may explain the nonsignificant effect of obesity we found. Minimizing the amount of time an obese individual spends supporting themselves on a single leg has been suggested as a mechanism to reduce muscular work while walking in individuals with obesity (Malatesta et al., 2009).

Weight loss and exercise have been shown to improve spatiotemporal gait characteristics in individuals with obesity. For example, 12-weeks of weight reduction exercise training has been shown to improve walking speed, step length, and step width in individuals with obesity (Jegede et al., 2017). However, the success of long term weight loss interventions are low (Barte et al., 2010). Thus, there is a need for future studies to examine interventions other than weight loss to combat the effects of obesity. Furthermore, the pool of data regarding the effects of obesity on gait remains limited and future studies are needed to understand whether spatial-temporal gait adaptations observed in individuals with obesity are mainly compensations directed at reducing metabolic cost, joint loading, and pain and/or reflect an underlying instability. Identification of additional biomechanical or neuromuscular factors (e.g., quadriceps function) affecting spatial-temporal gait characteristics may be used to improve interventions used to treat and manage obesity.

There are limitations that should be taken into considerations while inferring the results of this systematic review and meta-analysis. First of all, the studies included in this systematic review and meta-analysis are limited to those published in academic journals in the English language. Excluding unpublished data is known to increase publication bias, however, to limit bias we searched a large number of databases and excluded duplicate data. (Montori et al., 2000). Secondly, in a few cases we combined

study data by group and/or across a set of standardized walking speeds. While this technique allowed us to limit our sampling bias and include all eligible participants and walking trials from each study, it may have masked differences that may have otherwise existed between individuals with or without obesity. Finally, the large amounts of heterogeneity among the studies included in our outcome measures suggests the effect of obesity on spatiotemporal measures of gait is highly variable, and thus, our understanding of obesity is limited. However, we hope the current study can help guide researchers to improving the consistency of measures examined in future research.

On the whole, obesity reduced self-selected walking speed and step length at self-selected walking speeds, but increased step width at self-selected walking speed and the double-support period at self-selected and standardized walking speeds. The slower and more stable gait pattern adopted by individuals is likely a strategy to reduce joint loading and improve dynamic stability while walking. Exercise interventions geared at the treatment and management of obesity should consider and attend to such alterations for best clinical practice. Finally, the current review is restricted in part, by the limited number of studies reporting on spatial-temporal gait characteristics in individuals with obesity. More research is needed regarding the effects of obesity on gait.

CHAPTER III

KNEE EXTENSOR STRUCTURE & FUNCTION IN CHILDREN, ADOLECENTS, ADULTS, AND OLDER ADULTS WITH OBESITY: A SYSTEMATIC REVIEW AND META-ANALYSIS

Abstract

Purpose: To systematically review and analyze the effect of obesity on knee extensor structure and function in children, adolescents, adults, and older adults.

Methods: Experimental studies published in the English language examining knee extensor function in children 6-10 years old, adolescents 11-18 years old, adults 19-65 years old, older adults 65 years of age or older with or without obesity. A search for potential studies were performed in four electronic databases (PubMed, CINAL, Scopus, Cochrane Library), last searched on March 17th 2022. Risk of bias among the included studies was assessed by a 30-question epidemiological appraisal instrument that covers five domains: Study description, subject selection, measurement quality, data analysis, generalization of results. Data were extracted and meta-analyzed using a random effects model for our primary outcomes of knee extensor structure (muscle size and quality) and function (maximal force/torque, rapid torque, fatigue).

Results:

Included Studies: The search of the databases resulted in 6218 unique entries, 35 of which were included in the systematic review, and 29 in the meta-analyses.

Synthesis of Results:

Overall, obesity significantly increased absolute maximal measures of knee extensor function ($d_{pooled} = 1.33$, P = <0.001) and muscle size ($d_{pooled} = 2.69$, P = <0.030), but decreases relative maximal measures of knee extensor function ($d_{pooled} = -0.48$, P = <0.042) and the muscle quality ($d_{pooled} = -2.50$, P = 0.001). The effect of obesity on knee extensor structure and function was not reported or underreported in certain groupings and varied by age category.

Discussion: This systematic review and meta-analysis provides evidence that obesity increases absolute measures of maximal knee extensor function and size, but reduces relative measures of maximal knee extensor function and quality. However, the effect of obesity on knee extensor structure and function was underreported in certain groupings and varied by age category. The relative reduction in knee extensor function and quality is of importance to individuals living with obesity as they are associated with decreased mobility and increased incidence of osteoarthritis. Interventions aimed at treating and managing obesity should take note of these alterations. Finally, the studies reporting the effects of obesity on knee extensor structure and function is limited and additional research is needed.

Registration: This systematic review and meta-analysis was prospectively registered in the Open Science Framework (DOI: 10.17605/OSF.IO/ZGUK6).

Introduction

Obesity is a disease marked by an excessive accumulation of adipose tissue that can pose health risks to children, adolescents, adults, and older adults. Typically, adult obesity is defined as a body mass index (BMI; kg/m^2) of 30 or greater, whereas childhood and adolescent obesity lack a standard definition. The World Health Organization (WHO) defines obesity in children and adolescents as greater than two standard deviations above the WHO Growth Reference median (WHO, 2021). Similarly, the Centers for Disease Control (CDC) defines childhood and adolescent obesity as a score in the 95th percentile or greater on the BMI-for-age weight status table (CDC, 2021b). Alternatively, the International Obesity Task Force (IOTF) uses age and sex-specific cut-off points of BMI to define obesity in children and adolescents (Cole et al., 2000).

Obesity is largely caused by a positive energy imbalance brought on by ingesting calories at a greater rate than calories are being utilized. Globally, the prevalence of obesity has increased almost 80% from 1980 to 2015 (Chooi et al., 2019). As of 2015 107.7 million children and 603.7 million adults were estimated to be considered as obese (GBD, 2017). Importantly, 55% of children with obesity will go on to be obese in adolescence, and about 80% of adolescence with obesity will go on to be obese in adulthood (Simmonds et al., 2016). Health consequences of obesity include an increased risk for cardiovascular diseases, diabetes, cancer, and musculoskeletal disorders (WHO, 2021). More specifically, obesity appears to alter the structure (i.e., size and quality) and

contractile function (i.e., force/torque, power/rate of torque development (RTD), fatigue) of skeletal muscle.

Absolute strength, the maximum force or torque a muscle can generate irrespective of muscle or body size, appears to be increased in a muscle-specific manner with obesity. For example, previous studies have reported absolute knee extensor strength to be approximately 10-30% greater in individuals with obesity compared to those without obesity (Garcia-Vicencio et al., 2016; Hulens et al., 2001; Maffiuletti et al., 2007). Yet, knee flexor strength, upper-extremity strength, and specific handgrip strength measures are reported as not being different between individuals with and without obesity (Hulens et al., 2001; Lafortuna et al., 2005). The effect of obesity on knee extensor strength relative to the rapid parameters of muscle function, which include rate of force or torque production and power, is less clear. For instance, absolute knee extensor power is reported to be approximately 20% higher among individuals with obesity compared to those without obesity (Maffiuletti et al., 2007). At the same time, other studies have reported no differences in absolute isometric knee extensor RTD or power output of the lower extremity while consecutively jumping between individuals with and without obesity (Lafortuna et al., 2005; Vakula et al., 2019). However, once these measures are normalized to body mass or fat-free mass, the effect of obesity on muscle function becomes clearer.

In individuals with obesity, relative measures of strength and power likely have greater importance to activities of daily living, as the muscular forces needed to produce and control movement increase with mass. Once measures of skeletal muscle function are normalized to body mass or fat-free mass, strength and power appear to be reduced

among individuals with obesity. For example, the strength of the knee extensors is approximately 20-30% lower in individuals with obesity when normalized to body weight (Abdelmoula et al., 2012; Blimkie et al., 1990; Choi et al., 2016; Maffiuletti et al., 2007; Tsiros et al., 2013) and 6-18% lower when normalized to fat-free mass in comparison to normal-weight individuals (Hulens et al., 2001; Vakula et al., 2019). Obesity appears to have a similar effect on relative measures of power. For example, LaFortuna et al. 2005 reported lower extremity power output to be 40% lower per unit of body mass among individuals with obesity compared to normal-weight individuals. Additionally, Vakula et al. 2019 observed that knee extensor RTD relative to fat-free mass was roughly 19% less in individuals with obesity in comparison to those without. Moreover, volitional fatigue is greater in individuals with obesity. Maffiuletti et al. 2007 reported that the relative amount of torque lost during a fatiguing protocol was 13% greater in individuals with obesity in comparison to normal-weight controls. Although the exact mechanisms for impaired muscle contractile function as measured by muscle force, torque, power, and RTD are unknown, alterations in muscle structure may play a key role (Bollinger, 2017).

Commonly, the anatomical cross-sectional area (CSA) of load-bearing muscles and absolute levels of fat-free mass are increased with obesity (Choi et al., 2016; Hulens et al., 2001; Tsiros et al., 2013; Vakula et al., 2019). For example, fat-free mass is on average approximately 14% to 18.6% higher in individuals with obesity compared to normal-weight counterparts (Maffiuletti et al., 2007; Tsiros et al., 2013). Likewise, the CSA of muscles in the knee extensors and plantar flexors are significantly increased in individuals with obesity (Garcia-Vicencio et al., 2016; Vakula et al., 2019). Despite

exhibiting larger muscle mass/area, skeletal muscle quality (i.e., echo intensity grey scale, strength per unit of size, muscle tissue fat content) is decreased in individuals with obesity. For instance, when measured by the ratio of muscle strength (i.e., peak torque) to muscle CSA/volume, muscle quality is significantly reduced in individuals with obesity (Choi et al., 2016; Villareal et al., 2004). This loss of torque per unit of muscle mass likely stems from the three-fold increase in intermuscular fat volume reported in individuals with obesity, as the amount of lipid accumulation in the muscle and the ability of skeletal muscle fibers to produce force is inversely associated (Choi et al., 2016). This decrease in contractile function is due in part to the increased concentration of intramuscular fat in individuals with obesity (Goodpaster et al., 2000; Malenfant et al., 2001). Increased levels of intramuscular fat have been shown to increase the stiffness of the base material properties of the muscle, which has a negative effect on force production (Rahemi et al., 2015). Likewise, greater intramuscular fat infiltration measured indirectly using ultrasound echo intensity is associated with a lower internal knee extension moment in individuals with obesity walking at self-selected speed (Vakula et al., 2019). Together these findings suggest that the quality of the muscle, not just the size, influences muscle function that may result in aberrant muscle function (biomechanics) in individuals with obesity.

Currently, there are a limited number of studies reporting the effects of obesity on skeletal muscle structure and function. The studies that exist lack consistency in the muscle measured and the outcomes reported. For instance, some authors report outcomes for both the upper and lower extremity (Hulens et al., 2001), whereas others only report lower extremity measures (Capodaglio et al., 2009; Garcia-Vicencio et al., 2016).

Likewise, some authors report outcomes normalized to body mass (Capodaglio et al., 2009; Choi et al., 2016), and others choose to normalize their data to fat-free mass (Maffiuletti et al., 2008; Vakula et al., 2019). Although data regarding upper extremity muscle structure and function is limited, there does appear to be ample research on knee extensor or quadriceps function, but the existing research is contradictory. For example, several groups have shown that absolute knee extensor peak torque is increased with obesity (Choi et al., 2016; Hulens et al., 2001), while others have reported no difference between individuals with and without obesity (Rolland et al., 2007; Vakula et al., 2019). Reports are also conflicting on relative measures of knee extensor muscle structure and function (Choi et al., 2016; Maffiuletti et al., 2008; Tsiros et al., 2013; Vakula et al., 2019). There have been previous reviews about the effects of obesity on muscles' structure and function (Bollinger, 2017; Maffiuletti et al., 2013). However, to the best of our knowledge no study has quantified the effect of obesity on knee extensor structure and function using a systematic review and meta-analysis.

The knee extensors (i.e., quadricep muscles) play an important role during activities of daily living and during recovery of postural stability after an unexpected perturbation. For example, early during the stance phase of the gait cycle, the knee extensors act eccentrically to attenuate the forces acting on the knee joint and maintain postural stability (Whittle, 2014). Additionally, powerful corrective action of the knee extensors plays an important role during the recovery process from an unexpected slip during walking (Chambers & Cham, 2007). However, absent from the current literature are studies quantifying the collective effects of obesity on knee extensor structure and function. The results of this study will improve our understanding of the influence of

obesity on the structure and function of the knee extensors, allow healthcare professionals to better design efficacious treatments for those suffering from obesity, and guide researchers in the effort to improve the consistency in the measurements examined and reported in obesity and muscle-related research going forward.

The aim of this systematic review and meta-analyses was to examine the effect of obesity on absolute and relative measures of knee extensor muscle structure (muscle size and quality) and function (maximal force/torque, rapid torque, fatigue) in children, adolescents, adults, and older adults. Because systematic reviews and meta-analyses incorporate a much larger set of observations than any single study, this study will increase the understanding of obesity as a disease as a whole.

Methods

Protocol and Registration

The current systematic review and meta-analysis was created in agreement with the Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) statement (Moher et al., 2009). To ensure that our methods were reproducible and bias was limited in the methods we utilized in the review, this systematic review and meta-analysis was prospectively registered in the Open Science Framework prospective register of systematic reviews (DOI: 10.17605/OSF.IO/ZGUK6).

Eligibility Criteria

- *Types of studies*: Original research (i.e., cross-sectional studies, randomized control trials) that investigated at least one measure of knee extensor structure or function comparing individuals with obesity and normal weight. All publication dates were considered for inclusion, and included studies were limited to those published in peer-reviewed journals in the English language. If a randomized control trial or intervention study were to meet the eligibility requirements, only the baseline data from the study were included in the meta-analyses.

- *Types of participants*: Children 6-10 years old, adolescents 11-18 years old, adults 19-65 years old, older adults 65 years of age or older with or without obesity. Adults and older adults with normal weight or obesity were defined as having a BMI of 18.5-24.9 or greater than 30.0, respectively. Whereas normal-weight and obese children and adolescents were defined by any of the criteria set by the CDC, WHO, or the IOTF (CDC, 2021b; Cole et al., 2000, 2007; WHO, 2021). Participants with cognitive dysfunction, sensory impairments, or physical disabilities that could affect physical testing were excluded from being included in the current review.

- *Types of interventions*: Studies comparing measures of absolute or relative knee extensor structure and function in children, adolescents, adults, or older adults.

- *Types of outcome measures*: Primary outcome measures include absolute and relative measures of knee extensor muscle structure: size and quality; and contractile function: peak torque/force, power/RTD, fatigue.

Information Sources

The following electronic databases were searched to identify potential articles by two researchers (M.V. and Y.K.) working independently: PubMed (MEDLINE), CINAL (EBSCO), Scopus, and Cochrane Library. Likewise, the reference lists of articles related to our topic were manually searched to identify studies that may have been overlooked during the systematic searches. These searches were conducted from the commencement of the study through March 17th, 2022.

Search

The following search terms were utilized to look for potential articles in the electronic databases: (knee extens* OR leg extens* OR quadricep* OR lower-extremity OR lower-limb OR knee joint OR leg muscle) AND (muscle strength OR muscle power OR muscle weakness OR muscle deficit OR muscle performance OR muscle function OR muscle structure OR muscle quality OR muscle activation OR torque OR force OR rate of force development OR rate of torque development) AND (overweight OR obes* OR 'body mass index OR BMI).

Study Selection

Two reviewers (M.V. and Y.K.) working independently of one another performed the eligibility assessment. Disagreements that arose between reviewers were resolved with a single meeting in which the eligibility of articles were discussed until an agreement between reviewers was reached.

Data Collection Process

Data from the included studies were extracted by two independent reviewers (M.V., Y.K.). Extracted data were recorded onto a custom Microsoft Excel document. Authors of the included studies were not contacted for additional data, as our analysis was limited to published information sources.

Data Items

The following data were extracted from each of the studies included in the review and meta-analyses: (1) participant characteristics (sample size, age, sex, body mass index, body fat %); (2) type of intervention (limb analyzed (i.e., dominant), testing device, contraction type, angle of testing, data normalization); (3) absolute outcome measures (isometric peak torque, isokinetic peak torque, isotonic peak torque, isokinetic fatigue, isokinetic power, RTD, and muscle size); and (4) relative outcome measures (isometric peak torque, isokinetic peak torque, RTD, fatigue, and muscle quality).

Risk of Bias in Individual Studies

The methodological quality of the studies included in the systematic review were examined using a modified epidemiological appraisal instrument (EAI) developed by Genaidy et al. 2007. The original instrument consists of 43 items across five domains: study description, subject selection, measurement quality, data analysis, generalization of results. The modified version utilizes 30 criteria of the uppermost importance with respect to the included studies, similar to previous systematic reviews and meta-analyses (Lawrenson et al., 2019) see Appendix A for details of the instrument. Items were

marked as "Yes" (score of 2), "Partial" (score of 1), "No" (score of 0), "Unable to determine" (score of 0), or "Not applicable" (item excluded). The appraisal instrument has demonstrated good to excellent validity and inter-rater reliability (Kappa coefficient = 90% [CI; 87 to 92%]) (Genaidy et al., 2007). Two independent assessors (M.V. and Y.K.) blinded to the author and details of the publication assessed each study. Disagreements between assessors were settled during a single consensus meeting. The Cohen kappa statistic was used to calculate the level of agreement between assessors' scores for each question of the EAI (Viera & Garrett, n.d.). The general quality of the included studies was based on the average score across each item, with a maximum possible score of 2.0. Studies were classified by the following criteria: high quality ($\geq$1.4), moderate quality (1.1 to <1.4), or poor quality (<1.1) (Genaidy et al., 2007).

Summary Measures

The primary outcome measures were the standardized mean differences in measures of knee extensor muscle structure and function comparing children, adolescents, adults, and older adults with and without obesity.

Planned Methods of Analysis

First, the means and standard deviations of the outcome measures were extracted from the included articles. Next, the extracted data were entered into RevMan 5.4 software (Cochrane), where standardized effect sizes (Cohen d), effect size standard error, and the corresponding 95% confidence intervals were calculated.

When data was reported as a figure rather than in a table, Image J software (National Institutes of Health, Bethesda, MD) was used to digitize the mean and standard deviation of the outcome. When studies reported outcome data for both limbs, at multiple testing angles, or at various testing speeds a single study-wise effect size was calculated using a fixed-effects model in which the condition-wise effect sizes were weighted by their inverse variances (J. Higgins et al., 2021). A fixed-effects model was selected because a common effect of obesity was expected on outcome measures within a study. When studies reported multiple obese or normal-weight subgroups, they were combined according to the formula outlined in the Cochrane Handbook (J. Higgins et al., 2021). When studies reported outcome measures relative to body weight and fat-free mass, priority was given to the measure normalized to fat-free mass. This prioritization is due to differences in strength being largely attributable to individual differences in body composition, and fat-free mass is a gross indication of the amount of muscle mass an individual has (Lafortuna et al., 2005). When studies reported multiple measures of muscle quality (i.e., MRI, Ultrasound, Force/CSA), priority was given to imaging techniques (e.g., Ultrasound) over force/CSA measurements. Likewise, prioritization was given to isometric measures of contractile function when studies also reported isokinetic or isotonic measures. This prioritization was due to the contrived muscle actions experienced during isokinetic testing.

Overall and age categorized pooled effect sizes, 95% confidence intervals, and heterogeneity statistics were calculated using JASP (Version 0.16.3) for each of the knee extensor outcomes using a random-effects model with a restricted maximum likelihood approach (Harville, 1977). A random-effects model, rather than a fixed-effects model,

was selected due to the expected variability in experimental factors (i.e., limb or limbs analyzed, BMI group, knee extensor analysis instrumentation, etc.). The I^2 statistic, or the percentage of variability in the effect estimate due to heterogeneity rather than chance, were used to quantify inconsistencies across studies (J. Higgins et al., 2021). The heterogeneity level was categorized as follows:

- 0-40%: might be important;

- 30-60%: may represent moderate heterogeneity;

- 50 to 90%: may represent substantial heterogeneity;

- 75 to 100% considerable heterogeneity.

Data were categorized into two groups of related outcome measures:

- Absolute measures of knee extensor structure and function:

  - Maximal contractile function (i.e., peak force/torque)

  - Rapid contractile function (i.e., power, RTD)

  - Muscle size

- Relative measures of knee extensor function and structure:

  - Maximal contractile function (i.e., peak force/torque)

  - Rapid contractile function (i.e., power, RTD)

  - Muscle fatigue

  - Muscle quality

Measures of isometric, isokinetic, or isotonic peak torque/force were grouped together for analysis, as they aim to capture the "maximal or peak-capacities" of the knee extensors function. Similarly, measures of knee extensor power (i.e., isokinetic knee extension) and RTD (i.e., isometric knee extension) were grouped together for analysis,

as they aim to capture the "rapid or rate-based capacities" of the knee extensors contractile function. Absolute and relative outcome data are presented as separate forest plots to aid in visual examination of the data between individuals with and without obesity.

Risk of Bias Across Studies

The risk of publication bias were assessed visually using funnel plots and statistically using Egger's test (Egger et al., 1997).

Additional Analyses

In order to examine whether the summary outcome effects vary in relation to the age category of participants, a pre-specified subgroup analysis were conducted.

Results

Literature Search

The four databases that were searched resulted in 6218 distinctive articles, 35 of which met the inclusion criteria. No additional articles were identified through manual searching of related reference lists. See Figure 3-1 for the details of the full search strategy.

Figure 3-1

Search Flow Diagram of Article Inclusion Process
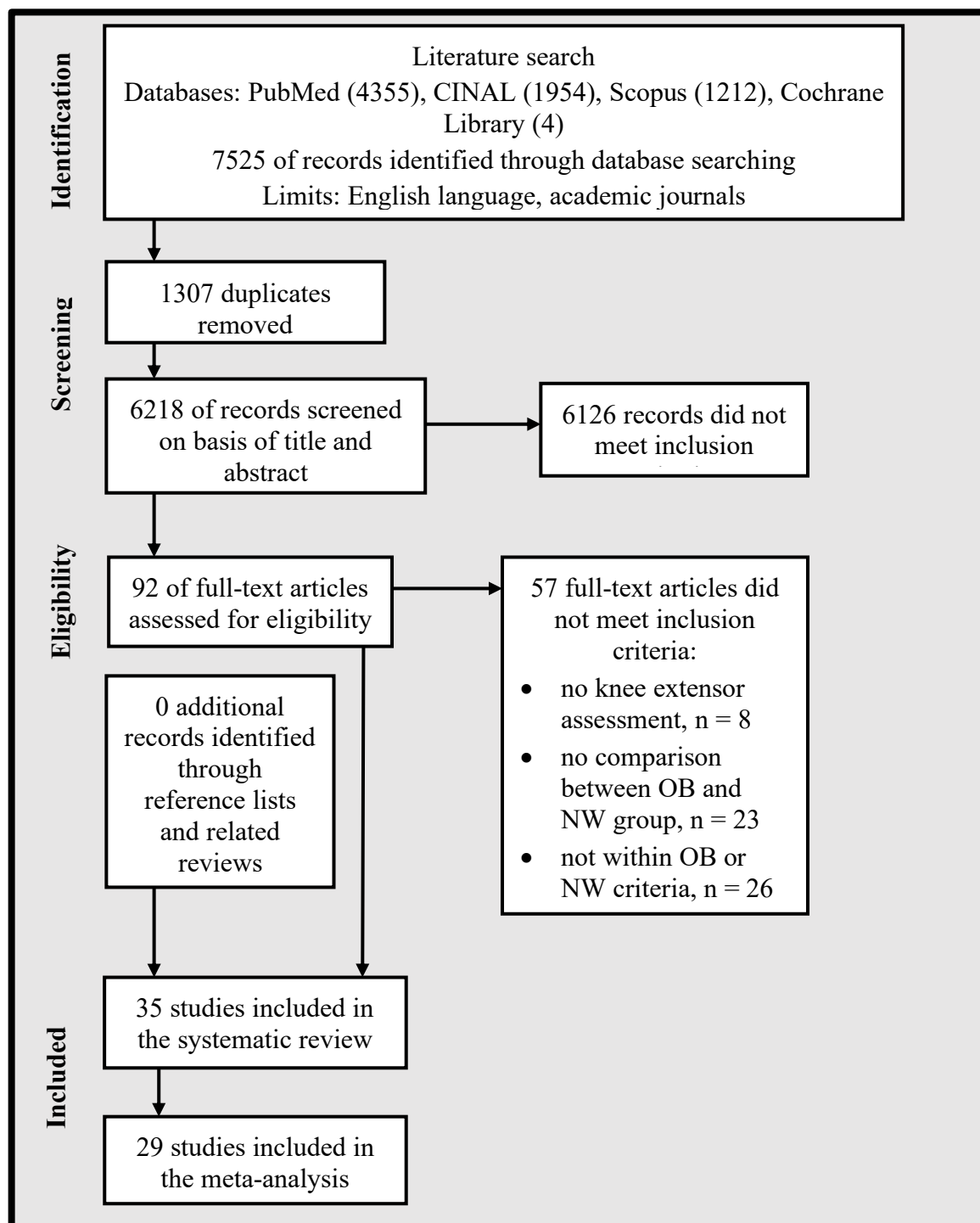
Note: OB obese, NW normal weight, BMI body mass index.

Assessment of Methodological Quality

The studies included in the systematic review (Appendix C) had a high average quality score of 1.53 ± 0.16 out of the possible 2.0 points with a range of $1.17 - 1.79$ points (Table 3-1). The item assessing environmental covariates and confounders was not applicable to any of the included studies. Six out of the 35 included studies reported reliability data for their outcome measures. Similarly, sample size calculations were only reported in eight of the 35 studies included in the final analysis. Agreement between raters ranged from strong (i.e., 0.81) to perfect, with an average Cohen Kappa value across all studies of 0.90 ± 0.04.

Table 3-1

Risk of Bias

Risk of bias assessment matrix. Study columns (left to right): Abdelmoula et al. 2015; Arieta et al. 2022; Briggs et al. 2019; Briggs et al. 2021; Capodaglio et al. 2009; Carvalho et al. 2015; Choi et al. 2016; Duan et al. 2018; Garcia-Vicencio et al. 2015; Garcia-Vicencio et al. 2016; Geirsdottir et al. 2019; Giuliani et al. 2020; Goodpaster et al. 2000; Hällsten et al. 2003; Herda et al. 2018; Herda et al. 2019; Hulens et al. 2001; Hulston et al. 2018; Kim et al. 2015; Koushyar et al. 2017; Lanzer et al. 2013; Maffiuletti et al. 2007; Maffiuletti et al. 2008; Muollo et al. 2021; Muollo et al. 2022; Pamukoff et al. 2019; Rastelli et al. 2015; Rolland et al. 2004; Tsiros et al. 2013; Tsiros et al. 2016; Vaccari et al. 2019; Vakula et al. 2019; Vakula et al. 2022; Waldburger et al. 2015; Yung et al. 2017.

Question	Percentage of Studies Scoring "NA"
Q1. Hypothesis/aim/objective described	57.1%
Q3. Main outcomes described	100.0%
Q4. Study design described	100.0%
Q5. Source of participant population described	60.0%
Q6. Participant eligibility criteria described	74.3%
Q7. Participation rates reported	100.0%
Q8. Characteristics of participants described	100.0%
Q11. Individual covariates an confounders described	62.9%
Q12. Environmental covariates & confounders (all NA)	0%
Q13. Statistical methods clearly described	65.7%
Q14. Main findings clearly described	100.0%
Q15. Estimates of random variability provided	100.0%
Q16. Estimates of statistical parameters	34.3%
Q17. Sample size calculation performed and reported	22.9%
Q18. Comparison group comparable	68.6%
Q19. Adequate participation rate	100.0%
Q20. Participants recruitment during the same time period (mostly UTD)	2.9%
Q21. Subject losses accounted for	100.0%
Q29. Observers blinded (mostly UTD)	5.7%
Q31. Outcome measures are reliable (mostly UTD)	17.1%
Q32. Outcome measures are valid (mostly UTD)	11.4%
Q33. Standard methods of assessment	94.3%
Q34. Observation made during the same time period (mostly UTD)	2.9%
Q35. History of disease and/or symptoms included in analysis	71.4%
Q36. Adjustment of individual covariates & confounders	77.1%
Q37. Adjustment of environmental covariates & confounders	0.0%
Q40. Outcome reported by level of exposure	2.9%
Q41. Outcome reported by subgroups	14.3%
Q42. Results are applicable to eligible population	100.0%
Q43. Results are applicable to other populations	100.0%

Average Quality Score (0-2): 1.58, 1.42, 1.72, 1.60, 1.46, 1.69, 1.25, 1.46, 1.38, 1.46, 1.67, 1.58, 1.44, 1.17, 1.54, 1.36, 1.46, 1.21, 1.63, 1.73, 1.50, 1.56, 1.38, 1.79, 1.79, 1.78, 1.38, 1.58, 1.62, 1.54, 1.63, 1.76, 1.67, 1.42, 1.42

Cohen Kappa Value: 0.93, 0.88, 0.92, 0.93, 0.87, 0.82, 0.82, 0.88, 0.93, 0.87, 0.93, 0.87, 0.82, 0.94, 0.89, 0.94, 0.94, 0.94, 0.86, 0.92, 0.86, 0.93, 0.88, 0.92, 0.91, 0.89, 0.87, 0.94, 0.93, 0.94, 0.92, 1.00, 0.92, 0.81, 0.88

"Yes" (2) = ■ ; "Partial" (1) = ▨ ; "No" (0) = ☐ ; "Unable to determine" = UTD ; "Not applicable" = NA

Characteristics of Studies

There were 1384 participants with obesity and 1632 with normal-weight among the 35 studies included in the systematic review (Table 3-2). Participants ranged in average age from eight to 80 years old with two studies reporting on children, eight on adolescents, 16 on adults, and nine on older adults (e.g., > 65 years). Participants were solely females in nine studies, entirely males in seven studies, and 17 were a mix of genders. Body fat percentage ranged from 26.6 - 47.9% for individuals with obesity and from 13.6 – 33.5% for individuals classified as normal-weight. Knee extensor function was measured by isokinetic dynamometry in 28 studies with the Biodex System III being the most utilized model. In all studies reporting isokinetic measures of knee extensor function, only concentric contractions were reported. Finally, at least one measure of knee extensor structure or function was normalized in 24 of the 35 studies included in the systematic review.

In order to reduce sampling bias, Vakula et al. 2019 was included in the meta-analysis, however, Vakula et al. 2022 and Pamukoff et al. 2020 were excluded for reporting similar outcomes from a similar sample. Likewise, Tsiros et al. 2013, Herda et al. 2018, Muollo et al. 2021, and Guiliani et al. 2020 were included in the meta-analysis whereas, Tsiros et al. 2016, Herda et al. 2019, Muollo et al. 2022, and Arieta et al. 2022 were excluded, respectively. Finally, absolute isometric peak torque from Garcia-Vicencio et al. 2015 was included but excluded from Garcia-Vicencio et al. 2016.

Table 3-2-A

Participant Characteristics and Study Details

	Sample Size		Age		Sex		BMI, kg/m²		Body Fatt %		Study Details				
Study	N OB	N NW	Age OB	Age NW	Sex OB	Sex NW	BMI OB	BMI NW	BF % OB	BF% NW	Limb analyzed	Testing device	Contraction Type	Angle of testing	Data Normalization
Abdelmoula et al. 2012	12	10	14.2 ± 1.4	14.4 ± 0.7	M 12/F 0	M 10/F 0	34.1 ± 5.4	19.4 ± 1.7	40.6 ± 6.8	14.9 ± 3.7	Dominant	Custom ergometer	Isometric	60°	PT to FFM
Arieta et al. 2022	19	22	69.1 ± 2.5	69.4 ± 2.1	M 19/F 0	M 22/F 0	33.7 ± 3.7	23.3 ± 1.5	36.7 ± 3.7	24.4 ± 6.3	Right	B-mode ultra sound	NA	NA	NA
Briggs et al. 2019	20	20	14.05 ± 2.09	14.10 ± 2.02	M 13/F 7	M 13/F 7	29.20 ± 2.16	20.36 ± 2.59	36.5 ± 7.3	21.9 ± 6.7	Dominant	Dynamometer	Isokinetic (150°/s)	NA	PT to BM
Briggs et al. 2021	24	24	14.13 ± 2.03	14.17 ± 1.97	M 16/F 8	M 16/F 8	29.21 ± 1.99	20.06 ± 2.50	36 ± 7	21 ± 7	Dominant	Dynamometer	Isokinetic (150°/s)	NA	PT to leg FFM
Capodaglio et al. 2009	20	14	29.1 ± 6.5	30.1 ± 4.7	M 0/F 20	M 0/F 14	38.1 ± 3.1	21 ± 1.6	NA	NA	Right and Left	Dynamometer	Isokinetic (60, 180, 240°/s)	ROM 90°	PT to BM
Carvalho et al. 2015	18	13	35 ± 5	32 ± 5	M 0/F 18	M 0/F 13	42.2 ± 6.6	21.6 ± 2.0	47.9 ± 3.3	29.1 ± 3.3	Dominant	Dynamometer	Isometric; Isokinetic (60°/s)	90° (isometric); ROM 20 to 90° (isokinetic)	PT and PW to BM
Choi et al. 2016	21	13	69 ± 2	70 ± 2	M 10/F 11	M 6/F 7	30 ± 0.43	22 ± 0.52	39 ± 1.2	32 ± 1.7	Right and Left	Dynamometer	Isokinetic	NA	PT to BW
Duan et al. 2018	29	30	72.4 ± 5.9	73.0 ± 5.5	M 13/F 16	M 15/F 15	37.0 ± 4.6	23.6 ± 1.8	NA	NA	Dominant	Dynamometer	Isometric	90°	NA
Garcia-Vicencio et al. 2015	12	12	13.9 ± 0.9	13.6 ± 0.8	M 0/F 12	M 0/F 12	32.1 ± 4.2	18.3 ± 1.3	38.2 ± 4.9	20.4 ± 2.9	Right	Dynamometer	Isometric	20, 40, 60, 70, 80, 90, 100°	NA
Garcia-Vicencio et al. 2016	12	12	13.9 ± 0.9	13.6 ± 0.8	M 0/F 12	M 0/F 12	32.1 ± 4.2	18.3 ± 1.3	38.2 ± 4.9	20.1 ± 2.9	Right	B-mode ultra sound; Dynamometer	Isometric	90°	PT to leg FFM
Geirsdottir et al. 2019	85	48	73.3 ± 4.8	74.1 ± 5.8	M 45/F 40	M 13/F 35	33.9 ±	23.0 ± 1.5	42.1 ± 5.8	33.5 ± 8.3	NA	Dynamometer	Isometric	NA	PT to BW
Giuliani et al. 2020	20	22	69.0 ± 2.4	69.4 ± 2.1	M 20/F 0	M 22/F 0	34.0 ± 3.8	23.3 ± 1.5	37.0 ± 3.9	24.4 ± 6.3	Right	B-mode ultra sound; Dynamometer	Isometric	60°	PT to BM
Goodpaster et al. 2000	15	9	36 ± 1 .3	30 ± 2.0	M 10/F 5	M 6/F 3	33.6 ± 0.8	23.4 ± 1.1	35.3 ± 1.9	14.9 ± 1.8	NA	Muscle biopsy	NA	NA	NA
Hällsten et al. 2003	9	11	30 ± 2	26 ± 1	M 9/F 0	M 11/F 0	36 ± 2	22 ± 1	NA	NA	Right	Dynamometer	Isometric	50°	NA
Herda et al. 2018	15	14	8.8 ± 0.4	8.7 ± 0.6	M 5/F 10	M 6/F 8	20.8 ± 2.3	15.8 ± 1.4	29.1 ± 2.9	18.0 ± 3.0	Right knee	Dynamometer	Isometric	90°	NA
Herda et al. 2019	12	14	8.8 ± 0.9	8.6 ± 1.1	M 6/F 6	M 6/F 8	21.8 ± 2.4	15.8 ± 1.4	29.3 ± 5.3	18.0 ± 5.2	Right	Dynamometer	Isometric	90°	NA
Hulens et al. 2001	173	80	39.9 ± 11.4	39.7 ± 12.2	M 0/F 173	M 0/F 80	37.8 ± 5.3	22.0 ± 2.2	46.7 ± 4.6	26.9 ± 5.0	Right and Left	Dynamometer	Isokinetic	NA	NA
Hulston et al. 2018	8	9	24 ± 2	27 ± 1	M 7/1	M 8/1	33.6 ± 1.2	23.5 ± 0.6	29.5 ± 1.7	13.6 ± 1.9	Dominant	Knee extension machine	Isotonic	NA	NA

OB obese, *NW* normal weight, *PT* peak torque, *PW* power, *RTD* rate of torque development, *FFM* fat free mass, *BF* body fat, *BM* body mass, *NA* not availiable

Table 3-2-B

Participant Characteristics and Study Details Continued

Study	N OB	N NW	Age OB	Age NW	Sex OB	Sex NW	BMI OB	BMI NW	BF % OB	BF% NW	Limb analyzed	Testing device	Contraction Type	Angle of testing	Data Normalization
	Sample Size		Age		Sex		BMI, kg/m²		Body Fatt %		Study Details				
Kim et al. 2015	57	60	47.1 ± 8.6	50.9 ± 9.3	M 57/F 0	M 60/F 0	33.3 ± 3.9	23.5 ± 1.3	26.6 ± 1.8	18.9 ± 0.5	NA	Dynamometer	Isometric; Isokinetic (60°/s)	60° (isometric) ; NA (isokinetic)	PT to leg FFM
Koushyar et al. 2017	20	20	45.3 ± 24.9	44.8 ± 25.8	M 0/F 20	M 0/F 20	32.8 ± 4.1	22.3 ± 4.6	38.95 ± 5.6	28.6 ± 7.6	Right	Dynamometer	Isokinetic (75°/s)	NA	PT to BM
Lazzer et al. 2013	11	10	29.5 ± 5.5	26.8 ± 10.2	M 0/F 11	M 0/F 10	43.2 ± 5.4	21.1 ± 2.4	53.2 ± 3.4	25.8 ± 4.9	Right and Left	Force sensor and strap	Isometric	70°	PT to leg FFM
Maffiuletti et al. 2007	10	10	25.3 ± 5.2	27.0 ± 4.1	M 10/F 0	M 10/F 0	41.3 ± 5.4	22.6 ± 1.1	NA	NA	Right	Dynamometer	Isometric; Isokinetic (60, 120, 180°/s)	40, 60, 80° (isometric); ROM 0 to 90° (isokinetic)	PT to FFM
Maffiuletti et al. 2008	10	10	15.6 ± 1.2	14.9 ± 1.1	M 10/F 0	M 10/F 0	34 ± 3	19 ± 1	NA	NA	Right	Dynamometer	Isometric; Isokinetic (180°/s)	40 and 80° (isometric); ROM 0 to 90° (isokinetic)	PT to FFM
Muollo et al. 2021	36	34	68.2 ± 5.3	69.4 ± 5.4	M 18/F 18	M 18/F 16	33.8 ± 3.6	23.6 ± 1.7	44.4 ± 8.1	29.4 ± 5.1	Right	Dynamometer	Isometric; Isokinetic (60, 90, 150, 210°/s)	30, 60, 75, 90°	PT to leg FFM
Muollo et al. 2022	55	34	67.8 ± 5.3	69.4 ± 5.4	M 25/F 30	M 18/F 16	33.0 ± 3.5	23.6 ± 1.7	NA	NA	Right	Dynamometer	Isokinetic (60, 90, 150, 180, 210°/s)	NA	PT to leg FFM
Pamukoff et al. 2020	48	48	22.8 ± 3.53	22.0 ± 2.83	M 24/F 24	M 24/F 24	33.1 ± 4.07	21.6 ± 1.77	37.9 ± 7.06	19.9 ± 6.54	Dominant	Dynamometer	Isometric	60°	PT and RTD to FFM
Rastelli et al. 2015	5	6	72.4 ± 2.3	72.7 ± 1.9	M 0/F 5	M 0/F 6	36.8 ± 1.9	24.3 ± 1.8	41.9 ± 2.9	33.4 ± 1.9	Dominant	Dynamometer	Isometric (90°); Isokinetic (60, 120, 180, 240°/s)	90°	NA
Rolland et al. 2004	215	598	80.0 ± 3.5	80.7 ± 4.1	M 0/F 215	M 0/F 598	31.9 ± 2.6	21.6 ± 1.8	45.2 ± 4.4	30.2 ± 7.5	Right and Left	Electronic statergometer	Isokinetic	UTD	NA
Tsiros et al. 2013	107	132	11.8 ± 0.1	12.0 ± 0.1	M 56/ F 51	M 76/F 56	29.6 ± 0.4	18.2 ± 0.2	45.4 ± 0.5	21.7 ± 0.6	Right and Left	Dynamometer	Isometric; Isokinetic (60°/s)	90° (isometric); ROM 95° (isokinetic)	PT to FFM
Tsiros et al. 2016	107	132	11.8 ± 0.1	12.0 ± 0.1	M 56/ F 51	M 76/F 56	29.6 ± 0.4	18.2 ± 0.2	45.4 ± 0.5	21.7 ± 0.6	Right and Left	Dynamometer	Isokinetic (60°/s)	ROM 95°	PT to FFM
Vaccari et al. 2019	15	13	25.20 ± 6.76	26.54 ± 8.24	M 12/F 3	M 10/F 3	43.05 ± 7.54	21.85 ± 3.17	44.72 ± 6.88	20.08 ± 5.24	Right	Custom ergometer	Isometric	70°	PT to thigh muscle volume
Vakula et al. 2019	48	48	22.8 ± 3.5	22.0 ± 2.6	M 24/F 24	M 24/F 24	33.1 ± 4.1	21.6 ± 1.71	37.9 ± 7.2	19.9 ± 6.6	Dominant	Dynamometer	Isometric	60°	PT and RTD to FFM
Vakula et al. 2022	48	48	21.90 ± 3.16	22.90 ± 3.13	M 24/F 24	M 24/F 24	33.03 ± 3.20	21.60 ± 3.16	37.92 ± 7.03	19.88 ± 7.03	Dominant	Dynamometer	Isometric	60°	PT and RTD to FFM x height
Waldburger et al. 2016	45	32	35.0 ± 1.7	38.7 ± 2.1	M 12/F 33	M 7/F 25	42.6 ± 0.9	23.0 ± 0.4	45.7 ± 0.9	25.2± 1.0	Right and Left	Dynamometer	Isometric	90°	PT to FFM
Yang et al. 2017	23	20	24.91 ± 5.65	23.55 ± 4.05	M 15/F 8	M 6/F 14	35.11 ± 17.59	21.63 ± 2.43	37.68 ± 6.13	20.34 ± 5.82	Right	Dynamometer	Isometric	NA	PT to BM

OB obese, *NW* normal weight, *PT* peak torque, *PW* power, *RTD* rate of torque development, *FFM* fat free mass, *BF* body fat, *BM* body mass, *NA* not availiable.

Additional Analysis

All included outcome measures (Garcia-Vicencio et al., 2016; Koushyar et al., 2017; Maffiuletti et al., 2007), muscle quality (Rastelli et al., 2015), peak torque (Garcia-Vicencio et al., 2015), and fatigue (Maffiuletti et al., 2008) were digitized from graphs.

The following subgroups were combined into a single group to maximize the number of participants included in the analysis and control for sampling bias using the Cochrane formula (J. Higgins et al., 2021) in the following studies:

- Men's and women's groups (Duan et al., 2018; Muollo et al., 2021, 2022).

- Older and younger adult groups (Koushyar et al., 2017).

- Participants with class II and class III obesity (B. Kim et al., 2015).

A single study-wise effect size was calculated using a fixed-effects model and then entered into the meta-analysis in the following studies to combine:

- Early and late   (Vakula et al., 2019).

- Right and left limb outcome measures (Tsiros et al., 2013; Waldburger et al., 2016).

- Isokinetic testing speeds (Capodaglio et al., 2009; Maffiuletti et al., 2007; Muollo et al., 2022; Rastelli et al., 2015).

- Isometric testing angles (Maffiuletti et al., 2007).

- Rectus femoris, vastus lateralis, and vastus medialis anatomical CSA (Garcia-Vicencio et al., 2016).

Absolute Measures of Knee Extensor Structure and Function

Obesity had a significantly increased absolute maximal measures of knee extensor contractile function with a pooled effect size of 1.33 (95% CI: 0.60, 2.06; P = <0.001; I^2 = 98%) for the 25 studies included in the analysis (Figure 3-2). The funnel plot was symmetrical and the Egger test for publication bias was nonsignificant (P = 0.509). By age category, studies of child obesity included one study, studies of adolescent obesity included five studies and with an overall significant effect size of 1.80 (95% CI: 0.25, 3.34; P = 0.023; I^2 = 97%), studies of adult obesity included 12 studies and had an overall significant effect size of 1.75 (95% CI: 0.48, 3.02; P = 0.007; I^2 = 98%), studies

of older adult obesity included seven studies with an overall non-significant effect size of 0.29 (95% CI: -0.35, 0.93; P = 0.372; I^2 = 94%).
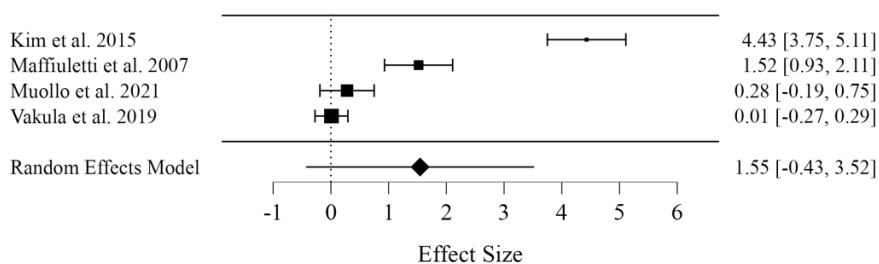
Figure 3-2

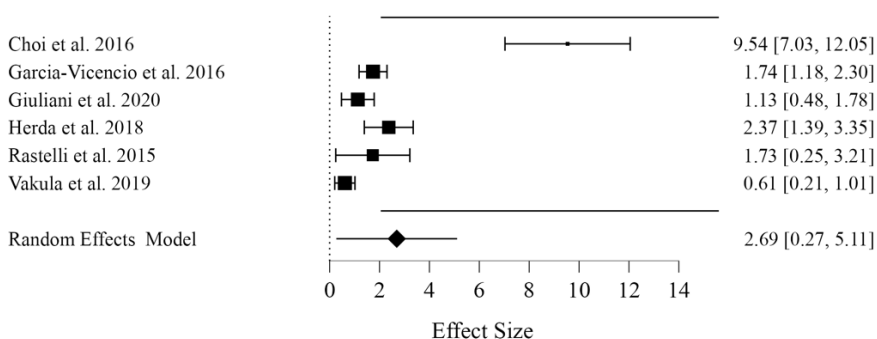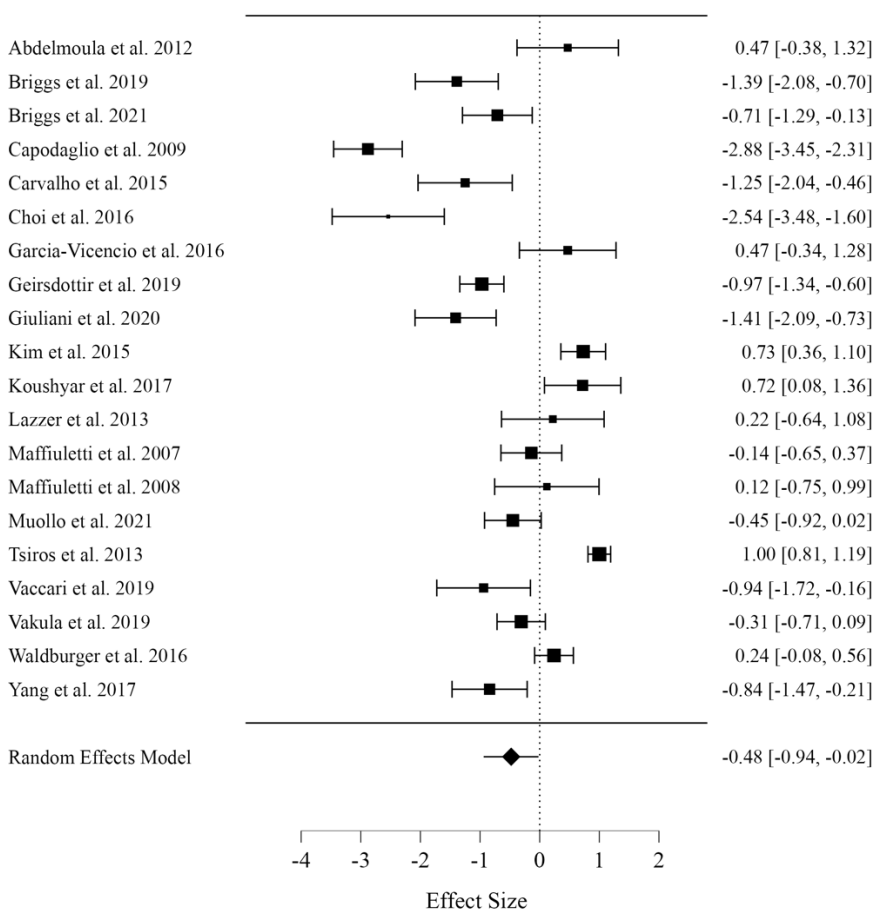*Forest Plot of Absolute Measures of Maximal Knee Extensor Contractile Function*

Study	Effect Size [95% CI]
Abdelmoula et al. 2012	0.89 [0.01, 1.77]
Briggs et al. 2019	0.17 [-0.45, 0.79]
Capodaglio et al. 2009	1.14 [0.71, 1.57]
Carvalho et al. 2015	1.34 [0.55, 2.13]
Choi et al. 2016	2.22 [1.33, 3.11]
Duan et al. 2018	-0.25 [-0.76, 0.26]
Garcia-Vicencio et al. 2015	2.61 [1.47, 3.75]
Geirsdottir et al. 2019	0.64 [0.28, 1.00]
Giuliani et al. 2020	0.20 [-0.41, 0.81]
Hällsten et al. 2003	1.45 [0.44, 2.46]
Herda et al. 2018	1.23 [0.43, 2.03]
Hulens et al. 2001	0.52 [0.25, 0.79]
Hulston et al. 2018	-0.21 [-1.16, 0.74]
Kim et al. 2015	6.74 [6.07, 7.41]
Koushyar et al. 2017	0.98 [0.32, 1.64]
Lazzer et al. 2013	1.35 [0.39, 2.31]
Maffiuletti et al. 2007	1.29 [0.89, 1.69]
Maffiuletti et al. 2008	0.87 [0.33, 1.41]
Muollo et al. 2021	0.14 [-0.33, 0.61]
Rastelli et al. 2015	-0.88 [-1.45, -0.31]
Rolland et al. 2004	0.24 [0.09, 0.39]
Tsiros et al. 2013	4.41 [4.18, 4.64]
Vaccari et al. 2019	0.08 [-0.66, 0.82]
Vakula et al. 2019	0.30 [-0.10, 0.70]
Waldburger et al. 2016	6.03 [5.28, 6.78]
Random Effects Model	1.33 [0.60, 2.06]

Obesity had a nonsignificant effect on absolute measures of rapid knee extensor

contractile function with a combined effect of 1.55 (95% CI: -0.43, 3.52; P = 0.125; I^2 =

99%) for the four studies included in the analysis (Figure 3-3). The funnel plot was

asymmetrical and the Egger test for publication bias was significant (P = 0.021). By age

category, there were no studies on child or adolescent obesity and one study on older

adult obesity, adult obesity included three studies and had an overall nonsignificant effect

size of 1.97 (95% CI: -0.57, 4.51; P = 0.128; I^2 = 99%).

Figure 3-3

Forest Plot of Absolute Measures of Rapid Knee Extensor Contractile Function

Kim et al. 2015		4.43 [3.75, 5.11]
Maffiuletti et al. 2007		1.52 [0.93, 2.11]
Muollo et al. 2021		0.28 [-0.19, 0.75]
Vakula et al. 2019		0.01 [-0.27, 0.29]
Random Effects Model		1.55 [-0.43, 3.52]

-1 0 1 2 3 4 5 6

Effect Size

Obesity significantly increased measures of knee extensor size with a combined

effect of 2.69 (95% CI: 0.27, 5.11; P = 0.030; I^2 = 98%) for the six studies included in the

analysis (Figure 3-4). The funnel plot was asymmetrical and the Egger test for

publication bias was significant (P = <0.001). By age category, there was one study each

on child, adolescent, and adult obesity, and thus no meta-analysis could be performed.

There were three studies on older adults with obesity with an overall nonsignificant effect

size of 4.02 (95% CI: -1.18, 9.23; P = 0.130; I^2 = 98%).

Figure 3-4

Forest Plot of Measures of Knee Extensor Size

	Effect Size
Choi et al. 2016	9.54 [7.03, 12.05]
Garcia-Vicencio et al. 2016	1.74 [1.18, 2.30]
Giuliani et al. 2020	1.13 [0.48, 1.78]
Herda et al. 2018	2.37 [1.39, 3.35]
Rastelli et al. 2015	1.73 [0.25, 3.21]
Vakula et al. 2019	0.61 [0.21, 1.01]
Random Effects Model	2.69 [0.27, 5.11]

Relative measures of knee extensor structure and function

Obesity significantly decreases relative measures of maximal knee extensor contractile function with a pooled effect of -0.48 (95% CI: -0.94, -0.02; P = 0.042; $I^2 =$ 94%) for the 20 studies included in the analysis (Figure 3-5). The funnel plot was symmetrical and the Egger test for publication bias was nonsignificant (P = 0.172). By age category, there were no studies on child obesity, six studies on adolescent obesity with an overall nonsignificant effect of 0.00 (95% CI: -0.73, 0.74; P = 0.992; $I^2 =$ 90%), ten studies on adult obesity with a nonsignificant effect size of -0.43 (95% CI: -1.12, 0.25; P = 0.211; $I^2 =$ 94%), and four studies on older adult obesity with a significant effect of -1.27 (95% CI: -2.08, -0.46; P = 0.002; $I^2 =$ 88%) on relative measure of maximal knee extensor function.

Figure 3-5

Forest Plot of Relative Measures of Maximal Knee Extensor Contractile Function

Abdelmoula et al. 2012	0.47 [-0.38, 1.32]
Briggs et al. 2019	-1.39 [-2.08, -0.70]
Briggs et al. 2021	-0.71 [-1.29, -0.13]
Capodaglio et al. 2009	-2.88 [-3.45, -2.31]
Carvalho et al. 2015	-1.25 [-2.04, -0.46]
Choi et al. 2016	-2.54 [-3.48, -1.60]
Garcia-Vicencio et al. 2016	0.47 [-0.34, 1.28]
Geirsdottir et al. 2019	-0.97 [-1.34, -0.60]
Giuliani et al. 2020	-1.41 [-2.09, -0.73]
Kim et al. 2015	0.73 [0.36, 1.10]
Koushyar et al. 2017	0.72 [0.08, 1.36]
Lazzer et al. 2013	0.22 [-0.64, 1.08]
Maffiuletti et al. 2007	-0.14 [-0.65, 0.37]
Maffiuletti et al. 2008	0.12 [-0.75, 0.99]
Muollo et al. 2021	-0.45 [-0.92, 0.02]
Tsiros et al. 2013	1.00 [0.81, 1.19]
Vaccari et al. 2019	-0.94 [-1.72, -0.16]
Vakula et al. 2019	-0.31 [-0.71, 0.09]
Waldburger et al. 2016	0.24 [-0.08, 0.56]
Yang et al. 2017	-0.84 [-1.47, -0.21]
Random Effects Model	-0.48 [-0.94, -0.02]

Effect Size

Obesity had no effect on relative measures of rapid knee extensor contractile function with a pooled effect of -0.34 (95% CI: -0.77, 0.08; P = 0.113; I^2 = 78%) for the five studies included in the analysis (Figure 3-6). The funnel plot was symmetrical and the Egger test for publication bias was nonsignificant (P = 0.151). By age category, there were no studies on child or adolescent obesity, four studies on adult obesity with an overall nonsignificant effect of -0.41 (95% CI: -1.00, 0.18; P = 0.173; I^2 = 86%), and one

study on the effect of older adult obesity on relative measures of rapid knee extensor function.

Figure 3-6

Forest Plot of Relative Measures of Rapid Knee Extensor Contractile Function
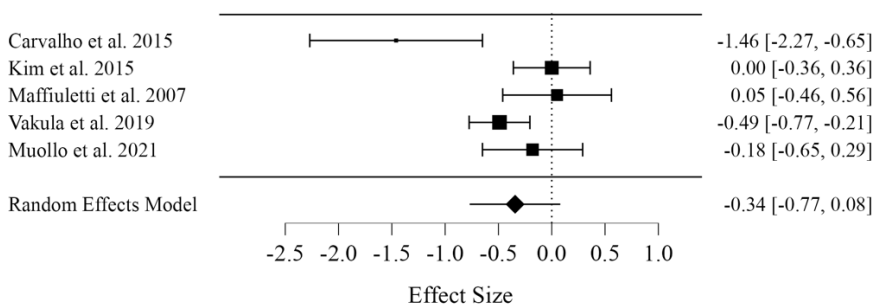
Obesity had no effect on relative measures of knee extensor fatigue with a pooled effect of -0.77 (95% CI: -1.87, 0.32; P = 0.166; I^2 = 88%) for the six studies included in the analysis (Figure 3-7). The funnel plot was symmetrical and the Egger test for publication bias was nonsignificant (P = 0.136). By age category, there were no studies on child obesity, two studies on adolescent obesity with an overall nonsignificant effect of -0.57 (95% CI: -1.43, 0.30; P = 0.198; I^2 = 49%), no studies on adult obesity, and four studies on older adult obesity with an overall nonsignificant effect of -0.90 (95% CI: - 2.62, 0.81; P = 0.301; I^2 = 92%) on relative measures of knee extensor fatigue.

Figure 3-7

Forest Plot of Relative Measures of Knee Extensor Fatigue
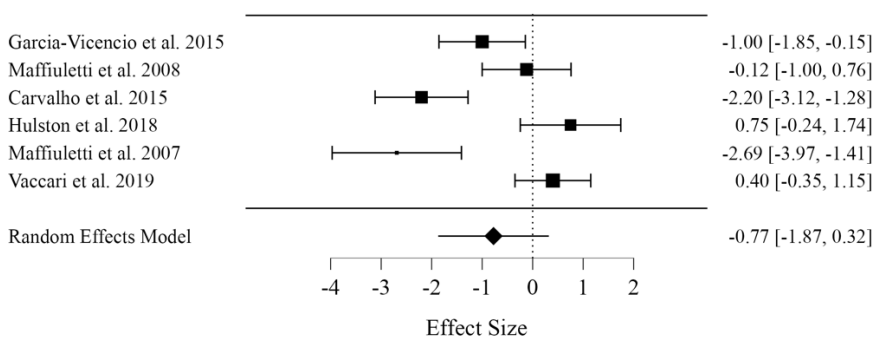
Obesity significantly decreases measures of knee extensor muscle quality with a pooled effect of -2.50 (95% CI: -4.04, -0.97; P = 0.001; I^2 = 95%) for the six studies included in the analysis (Figure 3-8). The funnel plot was asymmetrical and the Egger test for publication bias was significant (P = 0.002). By age category, there was one study on child obesity, no studies on adolescent obesity, two studies on adult obesity with an overall significant effect of -1.98 (95% CI: -3.59, -0.38; P = 0.015; I^2 = 84%), and three studies on older adult obesity with an overall nonsignificant effect of -3.03 (95% CI: -6.47, 0.41; P = 0.085; I^2 = 96%) on measures of knee extensor muscle quality.

Figure 3-8

Forest Plot of Measures of Knee Extensor Muscle Quality

Herda et al. 2018	-2.25 [-3.20, -1.30]
Goodpaster et al. 2000	-2.91 [-4.13, -1.69]
Vakula et al. 2019	-1.26 [-1.70, -0.82]
Choi et al. 2016	-6.70 [-8.53, -4.87]
Giuliani et al. 2020	-1.36 [-2.04, -0.68]
Rastelli et al. 2015	-1.26 [-2.45, -0.07]
Random Effects Model	-2.50 [-4.04, -0.97]

Effect Size
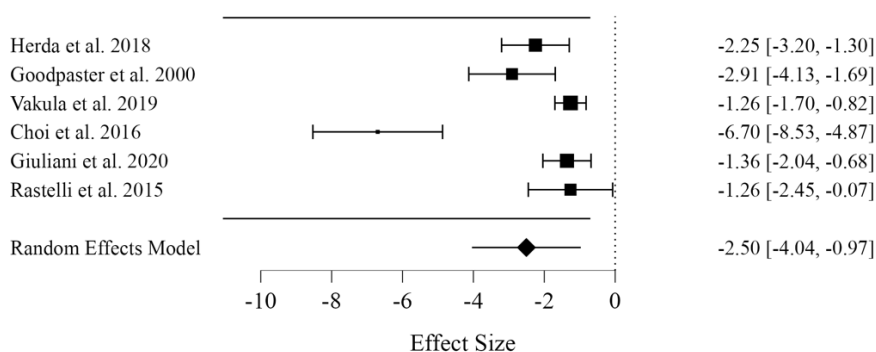
Discussion

The aim of this systematic review and meta-analysis was to evaluate the effect of obesity on absolute and relative measures of knee extensor muscle structure (muscle size and quality) and contractile function (maximal force/torque, rapid torque, fatigue) in children, adolescents, adults, and older adults. Overall, we included 35 studies in the systematic review and 29 studies into the meta-analysis. Our results, as a whole, suggest that knee extensor structure and function are altered with obesity. In particular, obesity significantly increased absolute maximal measures of knee extensor contractile force/torque and muscle size. Conversely, obesity decreased relative maximal measures of knee extensor contractile force/torque and muscle quality. Importantly, the effects of obesity on knee extensor structure and function differed by age category.

To the best of our knowledge, this is the first study to systematically review and analyze the effects of obesity on knee extensor muscle structure and function in children, adolescents, adults, and older adults. Overall, obesity increased absolute maximal measures of knee extensor contractile function, suggesting the peak torque or force production capabilities of the knee extensors, without respect to body size, are increased with obesity. This increase in absolute maximal contractile function is likely due to the increase in body mass that accompanies obesity which while weight bearing, acts as an overload stimulus for anti-gravity musculature such as the knee extensors. While this increase in contractile function has been suggested as a favorable adaptation with obesity (Garcia-Vicencio et al., 2016), our results suggest the effect of obesity on absolute maximal knee extensor contractile function varies with age. In adolescent and adults the effect of obesity on absolute maximal measures of contractile function was significant. However, in older adults the effect of obesity on absolute measures of maximal contractile function was non-significant, which is similar to findings noted in a previous narrative review by Bollinger (2017). The nonsignificant effect of obesity on absolute maximal measures of contractile function during older age may be influenced by reduced physical activity levels and/or sarcopenia, the age related loss of skeletal mass and strength (Rolland et al., 2004; Walston, 2012).

While absolute measures of knee extensor contractile function are increased with obesity, relative measures likely have greater importance to activities of daily living, mobility, and fall recovery. Overall, obesity decreased relative measures of maximal knee extensor function, suggesting that when scaled allometrically, the torque producing capabilities of the knee extensors is reduced. This reduction in knee extensor contractile

function is important considering their contribution to mobility and risk for knee osteoarthritis (McAlindon et al., 1993; Segal et al., 2010; Takagi et al., 2018). Furthermore, our subgroup analysis suggested the effect of obesity on relative knee extensor function was greater in older adults. A result, which may be influenced by a decline in central neurological dysfunction as well as sarcopenia (Carson, 2018). While further studies are needed to pinpoint the mechanisms behind this altered contractile function, surely, the increased muscle size but decreased muscle quality we found plays a role.

As a whole, obesity increased the size of the knee extensors, but decreased muscle quality. Our finding suggests that individuals with obesity have larger but lower quality knee extensor muscles when compared to individuals without obesity. The increase in the size of load bearing musculature such as the knee extensors is accepted in the literature as, an adaptation to the increased mass from excessive adipose tissue with obesity (Bollinger, 2017). However, it should be noted that the percentage of body mass coming from body fat was approximately 40% in individuals with obesity and 24% in individuals with normal weight on average, and therefore, the relative amount of fat-fee mass in the body is reduced with obesity. While the percentage differences in fat-free mass may in part explain the decrease in relative contractile function we observe in individuals with obesity, our results would also indicate that reduced muscle quality in this population should also be considered when explaining the decrements in relative contractile function.

The majority of studies reporting the effect of obesity on muscle quality either directly or indirectly measured the fat composition of the knee extensor muscles. In half

of the studies included in our meta-analysis (Giuliani et al., 2020; Herda et al., 2018; Vakula et al., 2019), muscle quality was measured via ultrasound echo intensity, an alternate measure of intermuscular fat accumulation (Choi et al., 2016). Therefore, our results suggest that the relative contribution of contractile tissue in the knee extensors is reduced with obesity. This increase in non-contractile adipose tissue within the muscle fiber is negatively associated with contractile function (Choi et al., 2016; Rahemi et al., 2015), and knee extensor function while walking (Vakula et al., 2019). However, the inclusion of fat into the muscle may explain, in part, the increase in muscle size and decrease in relative force seen with obesity.

Interestingly, we found no significant effect of obesity on absolute or relative measures of rapid knee extensor contractile function. Although measures of rapid knee extensor contractile function may be more relevant assessments to activities of daily living such as walking, they are under reported in the literature. The limited number of studies included in our analysis appear to suggest that absolute rapid contractile function is increased with obesity, whereas relative contractile function of the knee extensors is decreased with obesity. However, additional research is needed to reach such conclusions. It may be argued that the nonsignificant effect of obesity on rapid knee extensor function we reported was influenced by our inclusion of both isometric RTD and isokinetic power in our meta-analysis of rapid contractile function. Although RTD and power are both rate-based assessments of contractile function, they utilize different muscle actions (i.e., isometric VS concentric) and differences in muscle contractile function may have been concealed by our methods. Future research with increased

consistency in the outcomes reported are needed to better understand the effect of obesity on rapid knee extensor contractile function.

Although fatigue of the knee extensors has been suggested as a limitation during activities of daily living, we found that obesity had no overall effect on measures of knee extensor fatigue. Of the six studies we included in our analysis, four reported muscle fatigue was decreased with obesity (i.e., reduced ability), suggesting the effects of obesity on knee extensor fatigue is undecided. Among individuals with obesity, peripheral mechanisms such as the greater absolute maximal voluntary torque and proportion of fast twitch muscle fibers in the knee extensors are suggested as factors that may contribute to increased fatigue with obesity (Damer et al., 2022; Garcia-Vicencio et al., 2015; Hamada et al., 2003). However, additional research is needed to reinforce these findings. Alternatively, our nonsignificant result could have been influenced by factors such as age, sex, physical activity level, contraction type, testing methods, and severity of obesity, among other factors, which were not accounted for in our analysis. Future studies with improved controls for such factors are needed to fully understand the effect of obesity on muscle fatigue.

The following limitations should be considered when interpreting the results of this study. Firstly, the studies that included in this systematic review and meta-analysis were limited to those published in peer reviewed journals in the English language. Although excluding unpublished data may increase publication bias, we searched a large number of databases and excluded duplicate data in order to limit the bias introduced into the review (Montori et al., 2000). Secondly, in a limited number of studies, data were combined by group (e.g., male and female), testing speed, and/or testing angle. This

allowed us to include all eligible participants and experimental trials without introducing sampling bias, however, it may have disguised differences in knee extensor function and structure that may have existed. Thirdly, our review and analysis of knee extensor function was limited to concentric and isometric muscle actions. Yet, while walking the knee extensor predominantly use an eccentric muscle action to modulate forces acting on the knee joint and support the body (Vakula et al., 2022; Whittle, 2014). We found no studies that reported on eccentric muscle function, and thus, future studies are needed to examine the effect of obesity on eccentric muscle contractile function, as it may be more applicable to functional movements such as walking. Finally, the considerable levels of heterogeneity among the studies included in our outcomes implies that the effect of obesity on knee extensor structure and function is highly variable and our understanding of obesity is limited. Nonetheless, the results of this systematic review and meta-analysis will assists researchers seeking to improve the consistency of measures made and reported in future research.

In closing, the current systematic review and meta-analysis provides evidence that obesity increases absolute maximal knee extensor function and size, but a reduces relative maximal knee extensor function and quality. However, the effect of obesity on knee extensor size, quality, and absolute maximal contractile function appears to diminish with age. While the absolute torque producing capabilities and size of the knee extensors is increased with obesity, the relative reduction in knee extensor function and quality is of higher importance to individuals living with obesity while performing activities of daily living. Researchers and clinicians focusing on the treatment and management of obesity should consider interventions that improve the relative contractile

function and muscle quality of the knee extensors for optimal practice. Finally, relative to

the number of individuals effected by obesity, this systematic review and meta-analysis

was limited to a small number of studies. Additional research is needed to understand the

effects of obesity on muscle structure and function.

CHAPTER IV

GENERAL DISCUSSION AND CONCLUSIONS

This dissertation reported on two studies that analyzed the effect of obesity on (1) spatiotemporal gait measures in adults, and (2) knee extensor structure and function in children, adolescents, adults, and older adults. In the first study (chapter II) a systematic review and meta-analysis was conducted to examine the effects of obesity on self-selected walking speed and step length, step width, cadence, stance period, and double support period at standardized and self-selected walking speeds in adults. In a similar fashion for the second study (chapter III), a systematic review and meta-analysis was conducted to examine the effects of obesity on maximal and rapid knee extensor function, fatigue, muscle size, and muscle quality in children, adolescents, adults and older adults. The justification and need for these studies is based on the lack of consistency in the literature with regards to the effects of obesity on measures of gait, and knee extensor structure and function.

To the best of my knowledge, these are the first studies to systematically review and meta-analyze the effects of obesity on gait and lower-extremity muscle function. In the first study obesity was observed to reduce self-selected walking speed and step length, but increase step width and the double support period. The slower and more stable gait pattern adopted by individuals with obesity is suggested as a strategy to reduce the loads placed on the weight bearing joints and improve dynamic stability during the gait cycle (Vakula et al., 2019, 2022). These alterations to the gait pattern, at the cost of

mobility, allow individuals with obesity to limit metabolic costs and maintain a similar level of stability to normal weight individuals walking at self-selected speed (Browning et al., 2006; Liu & Yang, 2017; Russell EM et al., 2010; Vakula et al., 2022). Although the exact mechanisms behind the abnormal gait patterns common to individuals with obesity are unknown, altered knee extensor structure and function likely plays a role.

In the second study, it was observed that obesity increased absolute measures of maximal knee extensor function and muscle size, but decreased relative measures of maximal knee extensor function and muscle quality. The increase in absolute measures of maximal knee extensor contractile function is seen as a favorable adaptation of obesity, however, this increase in strength is likely due to the increased mass of obesity acting as a training stimulus for load bearing muscle. Furthermore, the effect of obesity on absolute maximal contractile function appears to diminish with age, suggesting that as people age issues such as sarcopenia and physical activity may effect muscle function more than obesity (Rolland et al., 2004; Walston, 2012).

Whereas muscle size and absolute measures of maximal knee extensor contractile function were increased with obesity, measures relative to body size or fat-free mass likely have greater importance to activities of daily living, mobility, and fall recovery. When scaled allometrically, our results suggest that relative measures of maximal knee extensor contractile function are decreased with obesity. This reduction in knee extensor quality and contractile function is important considering their contribution to mobility and risk for knee osteoarthritis (McAlindon et al., 1993; Segal et al., 2010; Takagi et al., 2018; Vakula et al., 2019). Furthermore, it is likely that the altered spatiotemporal gait parameters (e.g., reduced self-selected walking speed) we found in

the first study are influenced by the reduction in relative knee extensor function and structure we noted in the second study.

Overall, the number of studies on gait, and muscle size and function is limited in comparison to the incidence of obesity. Furthermore, studies included in the systematic reviews and meta-analyses were limited to published data which can increase the amount of publication bias in the reviews. While excluding unpublished data may increase publication bias, we included multiple large databases in our search and excluded duplicate study data to limit the effects of publication bias in our reviews. The considerable amounts of heterogeneity among the studies included in our meta-analysis suggests that we as researchers still have a lot to learn about the effect of obesity gait and muscle size and contractile function. While this dissertation as a whole contributes to the body of research on obesity, additionally, it will aide those designing valuable treatments for those suffering from obesity, and lead researchers to improving the consistency in the measurements examined and reported on with obesity. Clinicians and researchers focusing on the treatment and management of obesity should consider interventions that improve mobility and stability during gait, as well as, the relative contractile function and muscle quality of the knee extensors for optimal practice. Nonetheless, research on individuals with obesity is limited and additional research, with consistent outcomes and reporting is needed to better understand the effects of obesity on measures of gait and knee extensor structure and function.

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APPENDICES

Appendix A

Modified epidemiological appraisal instrument

Study description

Hypothesis / aim / objectives	1. Is the hypothesis/aim/objective of the study clearly described?
Outcome	3. Are the main outcomes clearly described?
Study design	4. Is the study design clearly described?
Study population	5. Is the source of subject population (including sampling frame) clearly described?
	6. Are the eligibility criteria for subject selection clearly described?
	7. Are the participation rate(s) reported? Is ascertainment of record availability described?
	8. Are the characteristics of study participants described?
Covariates and confounders	11. Are the important covariates and confounders described in terms of individual variables?
	12. Are the important covariates and confounders in terms of environment variables described?
Statistical Tests and Analysis Strategies	13. Are the statistical methods clearly described?
Results	14. Are the main findings of the study clearly described?
	15. Does the study provide estimates of the random variability in the data for the main outcomes or exposures (i.e. confidence intervals, standard deviations)?
	16. Does the study provide estimates of the statistical parameters (e.g. regression coefficients or parameter estimates such as odds ratio)?
	17. Are sample size calculations performed and reported?

Study's methodological quality

Subject selection	
Group comparability	18. Is the comparison/reference group comparable to the exposed/intervention/case group?
Participation rate/record availability	19. Is the participation rate adequate? Is the ascertainment of record availability adequate?
Time period	20. Are the study subjects from different groups recruited over the same period?
Subject losses/unavailability of records	21. Are subject losses or unavailable records after entry into the study taken into account?
Measurement quality	
Blind measurement	29. Are the observers blinded to: subject groupings when the exposure/intervention assessment was made or the disease status of subjects when conducting exposure assessment?

Outcome	31. Are the main outcome measures reliable?
	32. Are the main outcome measures valid?
	33. Are the methods of assessing the outcome variables standard across all groups?
Data analysis	
Observation period	34. Are the observations taken over the same time for all groups?
Covariates and confounders	35. Is prior history of disease and/or symptoms collected and included in the analysis?
	36. Is there adequate adjustment for covariates and confounders in terms of individual variables in the analyses?
	37. Is there adequate adjustment for covariates and confounders in terms of environment variables (other than exposure) in the analyses?
	40. Are outcome data reported by levels of exposure?
	41. Are the outcome/exposure data reported by subgroups of subjects?
Generalization of results	
	42. Can the study results be applied to the eligible population?
	43. Can the study results be applied to other relevant populations?

The following items from the original EAI were removed from analysis, as they were not applicable to the included studies 2, 9, 10, 22, 23, 24, 25, 26, 27, 28, 30, 38 and 39. Each item was scored as "Yes" (score of 2), "Partial" (score of 1), "No" (score of 0), "Unable to determine" (score of 0), or "Not applicable" (item excluded).

Appendix B

List of all studies included in the systematic reviews and meta-analysis in Chapter II

Agostini, V., Gastaldi, L., Rosso, V., Knaflitz, M., & Tadano, S. (2017). A Wearable

    Magneto-Inertial System for Gait Analysis (H-Gait): Validation on Normal Weight and

    Overweight/Obese Young Healthy Adults. *Sensors (Basel, Switzerland)*, *17*(10).

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    Could Be Applied to Evaluate the Resting and Walking Energy Expenditures of

    Individuals with Different Body Mass Index. *Turkiye Klinikleri Journal of Sports

    Sciences*, *12*(1), 84–93. ccm. https://doi.org/10.5336/sportsci.2019-71539

Arena, S. L., Garman, C. R., Nussbaum, M. A., & Madigan, M. L. (2017). Required friction

    during overground walking is lower among obese compared to non-obese older men, but

    does not differ with obesity among women. *Applied Ergonomics*, *62*, 77–82.

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    environment. *Journal of Neuroengineering and Rehabilitation*, *6*, 47.

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Appendix C

List of all studies included in the systematic reviews and meta-analysis in Chapter III

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Appendix D

Permission-to-use letter

School of Graduate Studies
Utah State University
0900 Old Main Hill
Logan, UT 84322-0900

Dear School of Graduate Studies,

I, Youngwook Kim, hereby grant permission to Michael Vakula to include the following research studies in his dissertation:

<Study 1>
Title: SPATIOTEMPORAL GAIT CHARACTERISTICS IN ADULTS WITH OBESITY: A SYSTEMATIC REVIEW AND META-ANALYSIS

<Study 2>
Title: KNEE EXTENSOR STRUCTURE & FUNCTION IN CHILDREN, ADOLECENTS, ADULTS, AND OLDER ADULTS WITH OBESITY: A SYSTEMATIC REVIEW AND META-ANALYSIS

Youngwook Kim
Signature

Youngwook Kim
Post-doctoral Fellow
Department of Kinesiology and Health Science
Utah State University

CURRICULUM VITAE

Michael Nicholas Vakula III, MS

Department of Kinesiology and Health Science
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EDUCATION

2017-Present	Ph.D. Disability Disciplines (Specialization: Pathokinesiology) Utah State University, Logan, UT Dissertation: Effects of Obesity on Gait and Knee Extensor Function and an Exercise Intervention for Individuals with Obesity
2017	M.S. Kinesiology California State University- Fullerton, Fullerton, CA Thesis: The Relationship Between Quadriceps Function and Gait Biomechanics in Young Obese and Normal Weight Young Adults
2015	B.S. Kinesiology California State University- Fullerton, Fullerton, CA

PROFESSIONAL EXPERIENCE

2017-Present	Graduate Research and Teaching Assistant Department of Kinesiology and Health Science, Utah State University, Logan, UT
2015-2017	Graduate Research and Teaching Assistant Department of Kinesiology, California State University- Fullerton, Fullerton, CA

TEACHING EXPERIENCE

Instructor of Record, Utah State University
KIN 6810: Research Methods in Kinesiology (2022)
PEP 6200: Biophysical Aspects of Physical Activity (2019, 2021)
PE 1550: Cycling (2021)

KIN 4400: Measurement and Evaluations in Kinesiology (2020)

Course Developer, Utah State University
PEP 6200: Biophysical Aspects of Physical Activity (2019)

Teaching Assistant, Utah State University
KNES 4400: Measurement and Evaluations in Kinesiology (2019)
PEP 3250: Anatomical Kinesiology (2017, 2018)

Guest Lecturer, Utah State University
PEP 3250: Anatomical Kinesiology (2017)

Instructor of Record, California State University- Fullerton
KNES 100: Physical Conditioning (2016)
KNES 102a: Beginning Jogging (2015, 2016)

Teaching Assistant, California State University- Fullerton
KNES 361: Principles of Human Movement (2015, 2016)
KNES 349: Statistical Methods in Kinesiology (2016)
KNES 461: Biomechanical Analysis of Human Movement (2016)

Guest Lecturer, California State University- Fullerton
KNES 202: Introduction to Kinesiology (2015, 2016)

PUBLICATIONS

Manuscripts in Refereed Journals:

1. **Vakula MN**, Garcia SA, Holmes SC, Pamukoff DN. Association Between Quadriceps Function, Joint Kinetics, and Spatiotemporal Gait Parameters in Young Adults with a without Obesity. *Gait & Posture*. 2022 Feb: 92: 421-427. https://doi.org/10.1016/j.gaitpost.2021.12.019

2. Kim, Y, **Vakula, MN**, Bolton DAE, Dakin CJ, Thompson BJ, Slocum TA., Teramoto, M, Bressel, E. Which Exercise Interventions Can Most Effectively Improve Reactive Balance in Older Adults?: A Systematic Review and Meta-Analysis. *Frontiers in Aging Neuroscience,* 2022 Jan: 13. https://doi.org/10.3389/fnagi.2021.764826

3. Cuthbert JM, Rogowski A, **Vakula MN**, Aguilar J, Kesler, K. The Missing Course: An Introduction to College Teaching for Graduate Instructors. *Journal on*

Empowering Teaching Excellence, 2021 Oct: 5(2)7.
https://digitalcommons.usu.edu/jete/vol5/iss2/7

4. Welsh PJ, Collier CG, Clement HM, **Vakula MN**, Mason JB. Cranial Cruciate Ligament Desmotomies in Sheep Resulting in Peroneus Tertius Injury. *Case Rep Vet Med*. 2021 Jul 21; 2021:2628791. https://doi.org/10.1155/2021/2628791

5. Garcia SA, **Vakula MN**, Holmes SC, Pamukoff DN. The Influence of Body Mass Index and Sex on Frontal and Sagittal Plane Knee Mechanics During Walking in Young Adults, *Gait & Posture*, 2021. 83:217-222. https://doi.org/10.1016/j.gaitpost.2020.10.010

6. Kim Y, **Vakula MN**, Waller B, Bressel, E. A Systematic Review and Meta-analysis Comparing the Effect of Aquatic and Land Exercise on Dynamic Balance in Older Adults. *BMC Geriatrics*, 2020 Mar: 20(1), 1-14. https://doi.org/10.1186/s12877-020-01702-9

7. Garcia SA, Moffit TJ, **Vakula MN**, Holmes SC, Montgomery MM, Pamukoff DN. Quadriceps Muscle Size, Quality, and Strength and Self-Reported Function in Individuals with Anterior Cruciate Ligament Reconstruction. *Journal of Athletic Training*. 2020;55(3):246-254. https://doi.org/10.4085/1062-6050-38-19

8. Pamukoff DN, **Vakula MN**, Holmes SC, Shumski EJ, Garcia SA. Body mass index moderates the association between gait kinetics, body composition, and femoral knee cartilage characteristics. *Journal of Orthoapedic Research: Official Publication of the Orthopaedic Research Society*. 2020 Mar. https://doi.org/10.1002/jor.24655

9. **Vakula MN**, Fisher KL, Garcia SA, Holmes SC, Post BK, Costa PB, Pamukoff DN. Quadriceps Impairment Is Associated with Gait Mechanics in Young Adults with Obesity. *Medicine and Science in Sports and Exercise*. 2019 May: 51(5): 951-961. DOI: 10.1249/MSS.0000000000001891

10. Pamukoff DN, Montgomery MM, Holmes SC, Moffit TJ, Garcia SA, **Vakula MN**. Association Between Gait Mechanics and Ultrasonographic Measures of Femoral Cartilage Thickness in Individuals with ACL Reconstruction. *Gait & Posture*. 2018 Sep; 65:221-227. https://doi.org/10.1016/j.gaitpost.2018.07.174

11. Bressel E, **Vakula MN**, Kim Y, Bolton DAE, Dakin CJ. Comparison of motor skill learning, grip strength and memory recall on land and in chest-deep water. *Plos one*. 2018 Aug:13 (8):e0202284. https://doi.org/10.1371/journal.pone.0202284

12. Pamukoff DN, Montgomery MM, Choe KH, Moffit TJ, Garcia SA, **Vakula MN**. Bilateral Alterations in Running Mechanics and Quadriceps Function Following Unilateral Anterior Cruciate Ligament Reconstruction. *The Journal of Orthopaedic and Sports Physical Therapy*. 2018 Dec; 48(12):960-967. https://www.jospt.org/doi/10.2519/jospt.2018.8170

13. Pamukoff DN, Montgomery MM, Choe KH, Moffit TJ, **Vakula MN**. Effect of Whole-Body Vibration on Sagittal Plane Running Mechanics in Individuals with Anterior Cruciate Ligament Reconstruction: A Randomized Crossover Trial. *Archives of Physical Medicine and Rehabilitation*. 2018 May; 99(5):973-980. https://doi.org/10.1016/j.apmr.2017.11.019

14. Pamukoff DN, Montgomery MM, Moffit TJ, **Vakula MN**. Quadriceps Function and Knee Joint Ultrasonography after ACL Reconstruction. *Medicine and Science in Sports and Exercise*. 2018 Feb;50(2):211-217. DOI: 10.1249/mss.0000000000001437.

15. Pamukoff DN, Dudley RI, **Vakula MN**, Blackburn JT. An evaluation of the heel strike transient in obese young adults during walking gait. *Gait & Posture*. 2016 Sep; 49:181-183. https://doi.org/10.1016/j.gaitpost.2016.07.001

Manuscripts in Review:

1. Kung, S, **Vakula MN**, Kim Y, England D, Bergeson J, Bressel E, Lefevre M, Ward R. No Effect of Flavonoid Supplementation on Exercise-induced Intestinal Injury, Permeability, and Inflammation in Recreational Cyclists: A Randomized Controlled Crossover Trial. *PLOS ONE*.

2. Kim, Y, Bolton DAE, **Vakula MN**, Bressel E. Comparison of aquatic exercise and land-based exercise on reactive balance in older adults: A randomized controlled trial protocol. Intended for *PLOS ONE*.

Manuscript in Preparation:

1. Kern A, Elwood M, **Vakula MN**, Kim, Y, Bressel E, Dakin CJ. Vestibular Influence on Balance Control during Stair Negotiation versus Walking and Changes with Aging. *Intended for Frontiers in Neurology.*

2. Kim Y, **Vakula MN**, Bressel, E. Effects of Aquatic Environment on Neuromuscular Functions: Towards Applications for Aquatic Exercise. *Intended for Journal of Strength and Conditioning Research.*

3. **Vakula MN**, Kim Y, Bolton DAE, Dakin CJ, Thompson BJ, Mason JB, Bressel E. Spatiotemporal Gait Characteristics in Adults with Obesity: A Systematic Review and Meta-Analysis. *Intended for Obesity Reviews..*

4. **Vakula MN**, Kim Y, Bolton DAE, Dakin CJ, Thompson BJ, Mason JB, Bressel E. The Effect of Obesity on Knee Extensor Structure and Function Across the Lifespan: A Systematic Review and Meta-Analysis. *Intended for Obesity Reviews.*

FELLOWSHIPS & AWARDS

1. Recipient, **Graduate Teaching Assistant of the Year** by the Department of Kinesiology and Health Science at Utah State University, 2021

2. Recipient, **Travel Award** by the Force and Motion Foundation, 2018

3. Recipient, **Board Fellowship** by the National Swimming Pool Foundation, 2018

4. Recipient, **Student Research Award** by the American College of Sports Medicine Biomechanics Interest Group, 2018

5. Finalist, **Student Research Award** by the American College of Sports Medicine Southwest Chapter, 2018

PRESENTATIONS

Invited Presentations:

1. **Vakula MN**. My Biggest Takeaways from ACUE's Course in Effective Teaching Practices as a Novice Instructor. Empowering Teaching Excellence Conference. Logan UT. August 18th, 2021.

2. **Vakula MN**. Explore College Teaching- Mini Learning Circle. Empowering Teaching Excellence Conference. Logan UT. August 18th, 2021.

3. **Vakula MN**. 5 Items that have empowered learning in my classroom as a graduate instructor. Empowering Teaching Excellence Conference. Logan UT. August 19th, 2020.

4. **Vakula MN**, Cuthbert JM, Arnold M. The ETE Explore College Teaching Track: Instructor training for graduate students. Empowering Teaching Excellence Conference. Logan UT. August 19th, 2020.

5. **Vakula MN**, Seeley MK, Pamukoff DN. Multifactorial contributors to knee articular cartilage health in normal and injured knees. Southwest American College of Sports Medicine Meeting. Newport Beach CA. October 25-26, 2019.

Refereed/Published Abstracts:

1. **Vakula MN**, Kim Y, Bressel E. Effects of the aquatic environment on maximal isometric muscle strength and rate of force development. NSCA National Conference. Las Vegas, Nevada. July 8th-11th, 2020. Accepted for poster presentation.

2. Kim Y, **Vakula MN**, Bressel E. Is maximal isometric strength altered during water immersion? NSCA National Conference. Las Vegas, Nevada. July 8th-11th, 2020. Accepted for poster presentation.

3. **Vakula MN**, Garcia SA, Holmes SC, Post BK Pamukoff DN. Quadriceps function is related to temporal gait characteristics in adults with obesity. *XXVII Congress of the International Society of Biomechanics/American Society of Biomechanics 43nd Annual Meeting*. Calgary, Canada. July 31-Agust 4, 2019. Accepted for poster presentation.

4. Holmes SC, **Vakula MN**, Moffit TJ, Pamukoff DN. Is quadriceps symmetry related to task symmetry in individuals with ACL reconstruction. *XXVII Congress of the International Society of Biomechanics/American Society of Biomechanics 43nd Annual Meeting*. Calgary, Canada. July 31-Agust 4, 2019. Accepted for poster presentation.

5. Pamukoff DN, **Vakula MN,** Shumski EJ, Post BK, Garcia SA, Holmes SC. Association between quadriceps function and femoral cartilage characteristics in young adults with obesity. *XXVII Congress of the International Society of Biomechanics/American Society of Biomechanics 43nd Annual Meeting*. Calgary, Canada. July 31-Agust 4, 2019. Accepted for oral presentation.

6. Dakin CJ, Kern A, Elwood M, **Vakula MN**, Kim Y, Bressel E. Vestibular Contribution to Balance Control during Stair Negotiation and Locomotion. *Society for Neuroscience*. San Diego, CA. November 3-7, 2018.

7. **Vakula MN**, Kim Y, Bolton DAE, Dakin CJ, Bressel E. Water immersion increases peak grip strength capacity in young adults. *World Aquatic Health Conference*. Charleston, SC. October 10-12, 2018. Accepted for poster presentation.

8. Kim Y, **Vakula MN**, Bolton DAE, Dakin CJ, Bressel E. Effects of partial water immersion on immediate and delayed memory recall. *World Aquatic Health Conference*. Charleston, SC. October 10-12, 2018. Accepted for poster presentation.

9. Post BK, **Vakula MN**, Garcia SA, Holmes SC, Pamukoff DN. The influence of body size, sex, and gait speed on plantar flexor moment and propulsive force. *American Society of Biomechanics 42nd Annual Meeting*. Rochester MN. August 8-11, 2018. Accepted for poster presentation.

10. Garcia SA, **Vakula MN**, Holmes SC, Post BK, Pamukoff DN. The influence of body mass index and sex on frontal and sagittal plane joint moments during walking. *American Society of Biomechanics 42nd Annual Meeting. Rochester MN. August 8-11, 2018.* Accepted for poster presentation.

11. Pamukoff DN, **Vakula MN**, Shumski E, Garcia SA, Holmes SC, Post BK. Frontal plan knee mechanics are associated with femoral cartilage echointensity in obese and normal weight young adults. American Society of Biomechanics 42nd Annual Meeting. Rochester MN. August 8-11, 2018. Accepted for poster presentation.

12. Pamukoff DN, Moffit TJ, **Vakula MN**, Holmes S, Garcia SA, Montgomery MM. Frontal plane knee mechanics during gait are associated with thinner femoral cartilage in females after ACL reconstruction. *National Athletic Trainer's Association Annual Meeting 69th Annual Meeting and Clinical Symposium*. New Orleans LA. June 26 – 29, 2018. Accepted for oral presentation.

13. Gardner LM, Montgomery MM, Garcia SA, **Vakula MN**, Moffit TJ, Holmes SA, Pamukoff DN. Influence of concomitant meniscal injury on self-reported disability and quadriceps function in individuals with ACL reconstruction. National Athletic Trainer's Association Annual Meeting 69th Annual Meeting and Clinical Symposium. New Orleans LA. June 26 – 29, 2018. Accepted for oral presentation

14. **Vakula MN**, Fisher KL, Costa PB, Pamukoff DN. Quadriceps impairment is associated with knee mechanics during gait In obese young adults. *American College of Sports Medicine Annual Meeting*. Minneapolis MN. May 29-June 2, 2018. Accepted for thematic poster presentation.

15. Pamukoff DN, Moffit TJ, **Vakula MN**, Holmes S, Garcia SA, Montgomery MM. Sagittal plane gait mechanics are associated with femoral cartilage thickness after ACL reconstruction. *American College of Sports Medicine Annual Meeting*. Minneapolis MN. May 29-June 2, 2018. Accepted for oral presentation.

16. **Vakula M**N, Fisher K, Costa P, Pamukoff, D. Quadriceps impairment is associated with knee mechanics during gait in obese young adults. *Southwest American College of Sports Medicine Meeting*. Long Beach CA. October 20-21, 2017. Accepted for oral presentation.

17. Garcia SA, Moffit TJ, **Vakula MN**, Holmes SC, Montgomery MM. Bilateral impairment in quadriceps function following ACL reconstruction. *Southwest American College of Sports Medicine Meeting*. Long Beach CA. October 20-21, 2017. Accepted for poster presentation.

18. Todoroff CM, Montgomery MM, Moffit TJ, **Vakula MN**, Holmes SC, Pamukoff DN. Increases in drop-landing ground reaction forces of uninvolved limbs following unilateral anterior cruciate ligament construction. *Southwest American College of Sports Medicine Meeting*. Long Beach CA. October 20-21, 2017. Accepted for poster presentation.

19. Holmes SC, Garcia SA, Moffit TJ, **Vakula MN**, Montgomery MM, Pamukoff DN. Influence of quadriceps strength symmetry of landing symmetry following ACL reconstruction. Southwest American College of Sports Medicine Meeting. Long Beach CA. October 20-21, 2017. Accepted for poster presentation.

20. Pamukoff DN, **Vakula MN**, Choe K, Moffit TJ, Montgomery MM. Impulsive loading during running following anterior cruciate ligament reconstruction. *American College of Sports Medicine Meeti*ng. Denver CO. May 30-June 3, 2017. Accepted for poster presentation.

21. Pamukoff DN, **Vakula MN**, Choe K, Moffit TJ, Montgomery MM. Ultrasonic evaluation of femoral cartilage thickness following anterior cruciate ligament

reconstruction. *Osteoarthritis Research Society International – 2017 World Congress on Osteoarthritis*. Las Vegas NV. April 27 – April 30, 2017. Accepted for poster presentation.

22. Pamukoff DN, **Vakula MN**, Choe K, Moffit TJ, Montgomery MM. Inter-limb comparison of knee mechanics during running following ACL reconstruction. National Athletic Trainer's Association Annual Meeting *68th Annual Meeting and Clinical Symposium.* Houston TX. June 26 – 29, 2017.

23. **Vakula MN**, Choe K, Moffit TJ, Montgomery MM, Pamukoff DN. Association between quadriceps function and femoral cartilage thickness in individuals with anterior cruciate ligament reconstruction. *Southwest American College of Sports Medicine Meeti*ng. Costa Mesa CA. Oct 21-22, 2016. Accepted for poster presentation.

24. Patterson J, **Vakula MN**, Choe K, Moffit TJ, Montgomery MM, Pamukoff DN**.** Interlimb comparison of vertical ground reaction force characteristics during running in individuals with anterior cruciate ligament reconstruction. *Southwest American College of Sports Medicine Meeti*ng. Costa Mesa CA. Oct 21-22, 2016. Accepted for poster presentation.

25. Choe K, **Vakula MN**, Moffit TJ, Montgomery MM, Pamukoff DN. Interlimb comparison of vastus lateralis architecture and geometry in individuals with anterior cruciate ligament reconstruction. *Southwest American College of Sports Medicine Meeti*ng. Costa Mesa CA. Oct 21-22, 2016. Accepted for poster presentation.

26. Moffit TJ, Choe K, **Vakula MN**, Montgomery MM, Pamukoff DN. Association between quadriceps function and running kinetics in individuals with anterior cruciate ligament reconstruction. *Southwest American College of Sports Medicine Meeti*ng. Costa Mesa CA. Oct 21-22, 2016. Accepted for poster presentation.

27. Pamukoff DN, Dudley RI, **Vakula MN**, Blackburn JT. Greater incidence of heel strike transient in obese compared to normal weight adults. *40th Annual Meeting of the American Society of Biomechanics*. Raleigh NC. Aug 2-5, 2016.

28. Pamukoff DN, Dudley RI, **Vakula MN**, Blackburn JT. A comparison of heel-strike transient identification methods in obese adults. *19th Biennial Meeting of the Canadian Society of Biomechanics.* Hamilton ON. *July 19-22, 2016.*

29. Choe K, Quon A, **Vakula MN**, Dudley RI, Pamukoff DN, Lynn SK. Sagittal plane biomechanics of the hip and knee joint in two squat variations. *39th Annual Meeting*

of the National Strength and Conditioning Association. New Orleans LA. July 6-9, 2016. Accepted for poster presentation.

SERVICE

Professional:

Ad Hoc Reviewer:
- International Journal of Exercise Science (2022)
- Empowering Teaching Excellence (2021-2022)
- Topics in Exercise Science and Kinesiology (2020)

University:

Utah State University, Logan Utah
- Empowering Teaching Excellence- Explore Subcommittee Member (2019-2022)
- Empowering Teaching Excellence- Conference Subcommittee Member (2020-2022)
- Empowering Teaching Excellence- Learning Circle Moderator (2021)
- Empower Teaching Excellence- Conference Moderator (2020)
- Academic and Instructional Services- Student Advisory Council (2019)
- Graduate Training Series- Panelist (2019)
- Student Research Symposium- Judge (2019)
- Voice of the Classroom Workshop- Canvas Product Development Team Consultant (2019)

California State University- Fullerton, Fullerton California
- Center for Sport Performance – Anaheim Ducks Performance Consultant (2015 – 2017)
- Center for Sport Performance – Nike Research Assistant (2016)
- Center for Sport Performance – PJF Performance, Performance Consultant (2015, 2016)
- Center for Sport Performance – Live Athos, Performance Consultant (2016)

Community:
- Volunteer Trail Builder, Trails Cache (2020-2022)
- Volunteer Course Builder/Setter, CROWBAR Backcountry Ski Race (2018, 2019)
- Mountain Bike Instructor, Non-Dot Adventures (2017)
- Volunteer Tail Builder, OC Parks (2015-2017)

STUDENT MENTORSHIP

- Jared Capell. Maters Independent Study, MS Kinesiology, Utah State University, Logan, UT

CERTIFICATIONS AND PROFESSIONAL MEMBERSHIPS

Certifications:

- Radiology Practical Technician, State of Utah Department of Commerce (2021 – Present)
- Certificate in Effective College Instruction- The Association of College and University Educators and the American Council on Education (2021)
- Teaching Scholar Certificate, Empowering Teaching Excellence (2021)
- Explore College Teaching Certificate, Empowering Teaching Excellence (2021)
- Basic Life Support for Healthcare Providers, American Red Cross (2015 – 2017)

Professional memberships:

- American College of Sports Medicine (2014 – 2020)
- American College of Sports Medicine South West Chapter (2014-2020)
- National Strength and Conditioning Association (2019-2021)
- American Society of Biomechanics (2019-2021)

CONTINUING EDUCATION

- Empowering Teaching Excellence
    - 8th Annual Conference, Logan UT, August 2021
- Empowering Teaching Excellence
    - 7th Annual Conference, Logan UT, August 2020
- The Association of College and University Educators
    - Effective Online Teaching Practices Course, August 2020-May 2021
- Empowering Teaching Excellence
    - E-Learn X Workshop, May 18-20 2020
- American College of Sports Medicine
    - South West Regional Meeting, Newport Beach CA, October 2019
- Empowering Teaching Excellence
    - 6th Annual Conference, Logan UT, August 2019
- International/American Society of Biomechanics
    - Annual Meeting, Calgary AB, July 2019
- Teaching for Learning Conference
    - 3rd Annual Meeting, Logan UT, March 2019
- Empowering Teaching Excellence

- E-Learning Workshop, May 21-23 2018
- American College of Sports Medicine
  - National Meeting, Minneapolis MN, May 2018
- American College of Sports Medicine
  - South West Regional Meeting, Long Beach CA, October 2017
- American College of Sports Medicine
  - National Meeting, Denver CO, May 2017
- American College of Sports Medicine
  - South West Regional Meeting, Costa Mesa CA, October 2015
- American College of Sports Medicine
  - South West Regional Meeting, Costa Mesa CA, October 2014

REFERENCES

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