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Soft Tissue Deformations Contribute to the Mechanics of Walking in Obese Adults

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Abstract

Obesity not only adds to the mass that must be carried during walking, but also changes body composition. Although extra mass causes roughly proportional increases in musculoskeletal loading, less well understood is the effect of relatively soft and mechanically compliant adipose tissue.

Purpose—To estimate the work performed by soft tissue deformations during walking. The soft tissue would be expected to experience damped oscillations, particularly from high force transients following heel strike, and could potentially change the mechanical work demands for walking.

Method—We analyzed treadmill walking data at 1.25 m/s for 11 obese (BMI > 30 kg/m²) and 9 non-obese (BMI < 30 kg/m²) adults. The soft tissue work was quantified with a method that compares the work performed by lower extremity joints as derived using assumptions of rigid body segments, with that estimated without rigid body assumptions.

Results—Relative to body mass, obese and non-obese individuals perform similar amounts of mechanical work. But negative work performed by soft tissues was significantly greater in obese individuals ($p = 0.0102$), equivalent to about 0.36 J/kg vs. 0.27 J/kg in non-obese individuals. The negative (dissipative) work by soft tissues occurred mainly after heel strike, and for obese individuals was comparable in magnitude to the total negative work from all of the joints combined (0.34 J/kg vs. 0.33 J/kg for obese and non-obese adults, respectively). Although the joints performed a relatively similar amount of work overall, obese individuals performed less negative work actively at the knee.

Conclusion—The greater proportion of soft tissues in obese individuals results in substantial changes in the amount, location, and timing of work, and may also impact metabolic energy expenditure during walking.

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CONFLICTS OF INTEREST

The authors are not aware of any conflicts of interest regarding this research.

SUPPLEMENTAL DIGITAL CONTENT

Supplemental Digital Content 1.pdf

Supplemental Digital Content 2.pdf

Keywords

biomechanics; joint loads; energy expenditure; gait; locomotion

INTRODUCTION

Obesity can greatly alter the mechanical demands for walking. Excess mass is well recognized to magnify the loads borne by the body, and thus require greater effort from the muscles. But obesity also entails a change in body composition. Adipose (fat) is a deformable tissue that can move relative to the skeleton and thereby potentially dissipate significant mechanical energy under the dynamic loads of locomotion (2,32), and thus require compensatory alterations in muscle power and timing. Although the mechanical demands of gait have been quantified in terms of rigid bodies, it remains unknown how adipose and other soft tissues affect the mechanics of walking, and potentially metabolic energy expenditure. We therefore seek to quantify the mechanical effects of soft tissues on the gait of obese and non-obese individuals. A better understanding of how excess soft tissue affects gait mechanics may ultimately lead to more effective physical activity-based weight management interventions.

Many of the mechanical demands of walking appear to scale proportionally with body mass. Obese individuals produce substantially greater absolute joint moments and powers to walk at the same speed as non-obese individuals (36). But in relative terms (per unit body weight), the moments and powers are quite similar (5). Obesity is also accompanied by some changes in step parameters, such as wider steps (5) and relatively longer double support times (3). But parameters such as step lengths and durations, and the basic joint kinematics are quite similar between obese and non-obese individuals walking at the same speed. The overall similarity may be explained by the pendulum-like behavior of the legs (29), because a pendulum's swing does not depend on its mass. In terms of pendulum dynamics, it is not unexpected for the kinematics to remain similar and for the joint moments and powers, as well as metabolic energy expenditure, to simply scale with overall body mass.

Adipose tissue may affect the mechanics of walking, because it is less stiff than muscle and bone in terms of material properties such as elastic modulus (18). The greater proportion of adipose tissue in obese individuals may therefore move differently compared to nonobese individuals, especially due to impacts such as the collision of the leg with ground. Impacts would be expected to mechanically excite the deformable tissue, which should respond with a damped oscillation and could have a variety of effects. A possible advantage is that an elastically supported load could reduce the demand on lower extremity muscles to absorb the impact actively (28). The elastic energy might even be returned to the body in a positive manner. However, because a possible disadvantage is that deformable tissue might undergo greater motion than the rest of the body, it may lead to greater energy dissipation than would be expected from pendulum-like motion alone. Unfortunately, the degree to which these effects occur is unknown, because most measures of walking mechanics rely on the method

of inverse dynamics (42), which quantifies joint moments and powers assuming that the body is composed of rigid segments.

The work of soft tissue deformations during locomotion can be estimated, albeit indirectly. One indicator is the net mechanical work over a stride, which should be zero over a stride of steady walking, but typically show more positive work than negative work using inverse dynamics (12, 44). Soft tissues may perform negative (dissipative) work that accounts for the discrepancy, which is indeed greater in obese than non-obese adults (14). This indicator does not, however, reveal the timing and fluctuations of such work within a stride. We have accordingly proposed an estimate of work performed by soft tissues, based on inconsistencies between inverse dynamics and the work performed on the body center of mass (COM) as measured by force plates (43,44). In non-obese individuals, these deformations can account for half of the negative work performed in the collision of each leg with the ground starting with heel strike (44). A greater proportion of soft tissues could amplify this effect.

The purpose of this study was to quantify the effect of obesity on soft tissue work during level walking at a constant velocity. We hypothesized that: 1) Soft tissue work during level walking would be greater in obese compared to non-obese adults. 2) Negative work performed by soft tissue during the first part of stance would be greater in obese compared to non-obese individuals. We tested these hypotheses by applying soft tissue work estimations to these two subject groups.

METHODS

We collected gait data from obese and non-obese participants walking on an instrumented treadmill. The measurements comprised standard recordings used in typical inverse dynamics procedures. To these data we applied a method to estimate the work performed by soft tissue deformations (43,44). These facilitated comparison of obese and non-obese participants while accounting for the absolute differences expected from body mass alone. Data used in this analysis has also been used in studies that have examined how obesity affects musculoskeletal function during walking (19,30,31).

Data collection

We collected motion capture and ground reaction force data from 11 obese (BMI > 30 kg/m²; 9 women) and 9 non-obese (BMI < 30 kg/m²; 5 women) individuals. Non-obese and obese participant characteristics (mean (S.D.)), respectively, were as follows: age (26.6 (6.3), 34.4 (7.4) years), height (1.69 (0.05), 1.68 (0.07) m), leg length (0.90 (0.03), 0.89 (0.04) m), body mass (62.8 (3.7), 94.8 (11.1) kg), and BMI (22.0 (1.0), 34.87 (4.1) kg/m²). Participants were in good health, with no known limitations to physical activity. Participants gave written informed consent approved by Colorado State University's Human Research Institutional Review Board.

Participants walked on a split-belt force-measuring treadmill (Bertec Corp., Columbus, OH) at 1.25 m/s with ground reaction forces collected at 1000 Hz by force platforms under each belt. Kinematic data was collected by a seven-camera motion capture systems (Nexus,

Vicon, Centennial, OH). Passive reflective markers were placed over the 7th cervical vertebrae, acromion processes, right scapular inferior angle, sternoclavicular notch, xyphoid process, 10th thoracic vertebrae, posterior–superior iliac spines, medial/lateral femoral epicondyles, medial/lateral malleoli, calcanei, first metatarsal heads, second metatarsal heads, and proximal and distal heads of the 5th metatarsals. To account for adipose tissue around the pelvis, virtual markers were placed on the anterior superior iliac spines and iliac crests using a digitizing wand (C-Motion, Germantown, MD). Marker clusters were placed on the thighs, shanks, and sacrum to aid in 3D tracking (31).

Work estimation procedure

We computed joint moments using standard inverse dynamics software (Visual3D, C-Motion, Germantown, MD). Body segment mass was estimated via dual x-ray absorptiometry (DXA, Hologic Discover, Bedford, MA) for both obese and non-obese participants. Marker motion data was filtered at 5 Hz and analog force data was filtered at 12 Hz. Joint powers were calculated at the ankle, knee, and hip for both legs, including six degrees of freedom for joint rotations and translations (10,17). The instantaneous powers at each point in the gait cycle were also summed across an entire leg to yield summed joint power.

Soft tissue work was quantified using methods detailed previously (43,44) and briefly summarized here. We seek to estimate the work resulting from deformation of soft tissues (Fig. 1A), potentially including not only fat but also the heel pad (20), viscera, vertebral discs, and even transverse deformations of muscle (as opposed to the work of muscle shortening or lengthening longitudinally, which is captured by joint work). This estimate is obtained from the difference between two measures of mechanical work during a stride: the summed joint powers from inverse dynamics (Fig. 1B) and the total mechanical work performed on and about the COM (Fig. 1C). The latter is the sum of the rates of work performed on the COM (termed *COM work rate* (15)), and of work performed to move body segments relative to the COM. The COM work rate for each limb was evaluated without rigid body assumptions, by taking the three-dimensional dot product of each limb's ground reaction force with the COM velocity, the latter estimated by integrating the total ground reaction force (11). This integration allows COM velocity to be estimated for periodic walking, without need for motion capture of rigid bodies. The work performed for body segment motions about the COM, termed *peripheral work rate*, was estimated from the time-derivative of the kinetic and rotational energy of the foot, shank, thigh, and trunk segments relative to the body COM, using the same body model from inverse dynamics (and therefore some rigid body assumptions). Integrals of these work rates produced COM work and peripheral work, which were added to yield total mechanical work, including soft tissue contributions. These are sometimes referred to as *external* and *internal work* of the body (16), terms that we avoid because of inconsistent definition in literature for “external” and “internal.”

The total mechanical work rate described above typically exceeds the summed joint powers, with the difference indicating work by soft tissue deformations (43,44). We have previously demonstrated that substantial soft tissue work occurs during collision and rebound during

walking in non-obese individuals (43). We hypothesize that obese individuals may exhibit greater negative work by soft tissues during collision and greater positive work during rebound.

The work rate measures were integrated to yield summary measures of work per stride. Integrals were performed over time to summarize the work performed by soft tissues over a stride and the work performed by lower extremity joints, by the individual joints and in total across joints. The summaries include net work over a stride, and positive and negative contributions to network. To indicate the timing of work, we also performed integrals over five phases of a stride, defined by positive and negative regions of the COM work rate, termed collision (approximately 0–18% of stride), rebound (18–30%), preload (30–50%), push-off (50–65%), and swing (65–100%) (15). The powers and their integrals were computed for each stride, and then averaged across an individual's strides (mean of 10.2 strides per participant with standard deviation of 7.3) to yield each subject's measures.

We normalized the various measures to account for differences in subject size, to allow for comparisons between obese and non-obese groups in relative terms. In contrast to absolute measures of work which have been well-characterized previously (e.g., 13), normalized measures are intended to reveal differences in work that are not explained by proportionate scaling of body mass or leg length (1,21). We therefore non-dimensionalized the work measures, using body mass (M), leg length (L), and gravitational acceleration (g) as base units. Thus, power was normalized by $Mg^{3/2}L^{1/2}$ and work was normalized by MgL . Leg length was estimated from DXA measurements. The mean non-dimensionalization constants for powers were 2758 W for obese participants and 1873W for non-obese participants, and the constants for work were 832J for obese participants and 571J for non-obese participants. For the convenient comparison with past literature, we also present most data using more familiar dimensional units such as power in the equivalent W/kg.

Statistical analysis

To test for statistical differences between groups, we used pooled-variance two-sample t-tests, comparing dimension less work measures across participant groups. All tests were two-tailed difference tests and significance was determined at a level of $\alpha = 0.05$.

RESULTS

We found large differences between obese and non-obese groups in the relative amount of work performed by soft tissues. This was primarily in the collision phase of gait, starting immediately after heel strike, where we observed considerably more negative work by soft tissues in obese participants. These differences occurred despite similarities in joint work performed over a stride, and the work performed on the COM, which were quite comparable between groups after accounting for differences in body size. We first summarize baseline results from inverse dynamics, to facilitate comparison with the previous literature. This is followed by estimates of mechanical work rates over time, and then summary measures with which the major statistical comparisons are performed (see Table, SDC 1, average work measures for non-obese and obese participants).

In terms of standard gait measures in the sagittal plane, there were few marked differences in the normalized trajectories for obese and non-obese participants (Fig. 2). Obese participants certainly produce greater absolute joint moments and torques than non-obese, but normalizing for body mass and leg length revealed the relative joint kinematics and kinetics to be quite similar. Stride length (1.37 (0.06), 1.36 (0.06) m, mean (S.D.) and stride time (1.09 (0.05), 1.07 (0.05) s) were similar in the non-obese and obese groups. The same was true for COM work rate and peripheral power (Fig. 3A), where normalization yielded quite similar trajectories. Comparison with joint powers (Fig. 3B) revealed that push-off positive power largely corresponded with the ankle, and to lesser degree the hip. rebound corresponded with knee power, and pre-load to ankle and hip. The summed joint powers generally corresponded well with total work rate (sum of COM and peripheral work), except for during collision, when it appeared to exceed joint work (Fig. 3C). Subtracting summed joint powers from total work rate yielded the soft tissue work rate (Fig. 3D), which was negative during most of collision and positive during rebound. However, obese participants appeared to have higher amplitude of soft tissue power during collision, rebound, and push-off.

We next quantitatively compare the difference in soft tissue work per stride between the two groups (Fig. 4). Obese participants produced about 83% more negative soft tissue work in obese during collision ($p = 0.0004$), and 71% less negative soft tissue work during push-off ($p = 0.0367$) than non-obese participants. The differences are attributable to changes in summed joint work, most dramatically during collision, where it was positive for obese participants and negative in non-obese participants.

Over the course of a stride, we found that obese individuals performed about 114% more positive and 34% more negative soft tissue work over a stride (Fig. 5A) compared to non-obese individuals (significant differences, $p = 0.0021$ and $p = 0.0102$, respectively) relative to body mass and leg length. There were no significant differences in positive and negative work between obese and non-obese groups in terms of COM work, peripheral work, and summed joint work, again in relative terms. Examining the net work over each stride, net joint work was significantly positive for both obese and non-obese groups ($p < 0.0001$ for both measures), about 33% and 32% of the total positive joint work respectively. Similarly, the net soft tissue work was also significantly negative ($p < 0.0001$ for both measures), about 52% and 71% of the total negative soft tissue work, respectively.

Examining the joints individually (Fig. 5B), a notable difference between groups was that the obese group performed about 21% less negative knee work ($p = 0.0215$) and 27% more positive knee work ($p = 0.0145$). There were no significant differences between groups in positive and negative work for any other joint. There was also no significant difference in net work at the ankle and hip. At the knee, obese individuals performed about 93% less net work ($p = 0.0057$). This appears to be associated with a 15% lower knee flexion rate (defined in Fig. 1 knee angle inset; 0.108 vs. -0.128 for non-obese, $p = 0.039$) and reduced knee torque (Fig. 1, middle) during collision for obese compared to non-obese groups.

DISCUSSION

Our results show that obese individuals perform more negative and positive soft tissue work than non-obese individuals over a stride. Soft tissue work exhibited much greater amplitude in obese individuals, with about 34% more negative work per stride. The amount was approximately equivalent to the negative work of the summed lower extremity joints (Fig. 5A) and larger than any individual joint (Fig. 5B). As hypothesized, much of the negative work occurred in the collision following heel-strike, where obese individuals perform 85% of the required negative work using soft tissue instead of joints, compared to 67% for non-obese individuals. The additional soft tissue mass in obese individuals may reduce the work done by knee extensor muscles during early stance, which may lead to a relative reduction in the metabolic cost of walking. In addition, greater negative soft tissue work during collision may increase the amount of energy dissipated by soft tissue during impacts, which may, in turn, affect the loading across lower extremity joints.

Our observations are based on indirect measures of soft tissue work. Their simplest indicator of soft tissue work is that the net joint work over a stride of steady gait is not measured to be zero as it should. That mismatch (Fig. 5A), also observed by DeVita et al. (14), implies that inverse dynamics fails to account for some negative work, but does not indicate its amplitude or timing. Our measures suggest that both negative and positive work are unaccounted for, roughly corresponding to the collision and rebound of the body COM. The amplitude of missing work in obese individuals was much greater, and its timing somewhat slower, as would be expected from a greater proportion of adipose tissue (Fig. 3D and 4).

The soft tissue work rate resembled a damped oscillation. Heel strike entails a large transient in ground reaction force, which would be expected to mechanically excite such an oscillation, where soft tissues perform net negative work. We also observed some positive work from soft tissues occurring immediately after the negative collision work, and in much smaller amplitude, consistent with a viscously damped response. The natural frequency of that oscillation appeared to be somewhat slower in obese individuals than non-obese individuals, also consistent with a greater mass proportion and/or compliance of soft tissue. The overall effect was that obese individuals appeared to shift both negative and positive joint work toward soft tissues.

We also observed non-zero soft tissue work during Push-off, in the form of negative and positive fluctuations (Fig. 3D). Much of this work is potentially attributable to the foot, where activity of intrinsic muscles (25), motion of the metatarsophalangeal joint, and deformation of heel pad and plantar tissues (26,27) yield a combined foot power profile (37,40,41) that is qualitatively similar to the soft tissue push-off contributions computed in this study. Some of the observed work may in fact be performed actively by muscle (25), but since foot work was not explicitly estimated in this analysis, their contributions get lumped into the soft tissue estimate.

There were also differences in joint work between the two groups. In non-obese individuals, active positive work is largely performed about the joints, especially the ankle, but the negative work is shared between joints and passive soft tissues (43). The greater proportion

of relatively soft adipose tissue in obese individuals appears to perform a greater proportion of the negative collision work, and may reduce the proportion performed actively by knee muscles during that phase. DeVita and Hortobágyi (13) previously reported less knee flexion in obese individuals yet similar absolute knee joint power, meaning that joint power did not scale with body mass. Our measures are largely consistent with those findings (e.g., 15% lower knee flexion rate in obese individuals during collision) and suggest that soft tissues may offload the knee musculature for energy dissipation. Indeed, an analogous mechanism has been proposed (28) to explain why backpack loads can be carried with relatively less metabolic energy if they are carried on springs (35). This should not, however, be regarded as net advantage, because the knee also performed more positive work and the ankle and hip exhibited subtler shifts in timing and amplitude (Fig. 5), such that the overall joint work was actually relatively similar between groups.

The altered body loads of obesity may have implications for energy expenditure. To gain further insight into metabolic rate, we performed a meta-analysis of previous literature to compare the cost of walking in obese individuals against non-obese walking with added loads (Fig. 6), as a function of weight gained from either fat or from carrying a load. Data from both groups were normalized using an approximately equivalent “unloaded body mass,” which for load carrying studies is simply each (non-obese) subject’s body mass. But for obesity studies, this corresponds to the body mass a person would have if they had the same body fat percentage as non-obese individuals, with all of their lean mass assumed to be part of “unloaded body mass.” For both types of studies, we plotted net metabolic rate for walking (subtracting the cost for standing from the gross cost of cost for walking and normalizing by unloaded body mass and leg length) against the loaded body mass (as a fraction of unloaded mass). This comparison effectively treats obese individuals as carrying an added load of adipose tissue beyond the “unloaded body mass,” subject to assumptions regarding the average body fat percentage of non-obese participants (see Table, SDC 2, data used to compare load carriage metabolic studies to obese metabolic studies). A linear regression from each data set shows several load carrying studies to have a steeper increase in energy expenditure with mass, compared to two obese data sets (6,9). This is especially true when loads are carried on the legs (8). Although there is considerable variation between different studies, it might indeed be relatively economical to carry load as soft adipose tissue rather than rigid weights.

There are a number of limitations to this study. Soft tissue work is an indirect estimate based on three complementary work measures, COM, peripheral, and inverse dynamics, all of which are subject to assumptions and experimental errors (43,44). We typically expect COM work to be relatively accurate because it relies on few assumptions other than periodic gait and can be verified by checking for zero net work. Our COM observations appeared consistent with previous data (7), although we did observe slightly non-zero net COM work over a stride (Fig. 5), which indicates a small bias in force recordings or energy exchange with the treadmill (38). The combined soft tissue work estimate method can be tested in tasks such as jump landing, where the total work is a known quantity for reference (44). Those comparisons reveal the soft tissue methodology to be quite self-consistent. Comparatively, inverse dynamics joint work and peripheral work have greater variability due to non-rigid bodies and imperfect motion capture. We used a custom marker set that

attempts to improve capture of hip motion (31), which can be particularly challenging with obese participants, and also used six degree-of-freedom joint power calculations to account for errors in joint center location. There is no method to independently verify inverse dynamics, but we found the observed trajectories to qualitatively agree well with previous literature (5,13).

There are also some limitations due to our participant pools. In particular, our obese subject population contained fewer males than females, and relatively young adults. Females generally have a greater proportion of adipose tissue mass (i.e. greater body fat %), and this mass is distributed more around the pelvis and thighs compared to the waist in males (24). While the greater proportion of females may magnify the effect of soft tissues seen in our analysis, the more peripheral distribution of body fat in females may also affect soft tissue work contributions, due to it undergoing different amounts of deformation than body fat at the waist. These and other effects may contribute to gender effects that have been indicated for metabolic energy expenditure during walking in obese individuals (4). Clearly, a future study using a larger, more diverse sample is needed to determine whether soft tissue work during walking varies with gender, distribution of adipose tissue, and age.

Taking into account these limitations, we find potential advantages and disadvantages to soft tissue work. Advantages include reduction of the negative work performed actively about the joints and an additional passive contribution to the redirection of the body COM during the step-to-step transition. Adipose tissue can presumably store and return mechanical energy without metabolic energy expenditure. This could potentially make it energetically more economical to carry adipose than an equivalent amount of rigid load. But there are also potential disadvantages, because some of the soft tissue work may increase the strain borne by articular cartilage and vertebral discs, and repeated loading may have degenerative effects contributing to osteoarthritis and other musculoskeletal ailments in the obese population (20). There also remains the overall greater load on the musculoskeletal system: neither muscle nor bone strength scale in direct proportion to body mass (23,34), and therefore these tissues may experience greater strain despite off-loading by soft tissues. As our understanding of soft tissue contributions to the mechanics of walking improves, it may become possible to take advantage of the capacity of these tissues to store and return energy. This could allow obese individuals to walk relatively economically, thus increasing their likelihood of participation in physical activity-based weight management programs.

SUMMARY

Obesity substantially increases the amount of negative work performed by soft tissues (and to lesser degree, positive work). The increase is most substantial during early stance, suggesting soft tissue helps dissipate more energy during impacts. This may help reduce the loading on the joints, especially the knee, although overall effects of increased body mass may still have degenerative consequences.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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REFERENCES

1. Alexander, RM. Mechanics and energetics of animal locomotion. London: Chapman and Hall; 1977. p. 376
2. Alonso F, Del Castillo J, Pintado P. Motion data processing and wobbling mass modelling in the inverse dynamics of skeletal models. *Mech Mach Theory*. 2007; 42:1153–1169.
3. Błaszczyk JW, Plewa M, Cie linska-Swider J, Bacik B, Zahorska-Markiewicz B, Markiewicz A. Impact of excess body weight on walking at the preferred speed. *Acta Neurobiol Exp (Wars)*. 2011; 71(4):528–540. [PubMed: 22237498]
4. Browning RC, Baker EA, Herron JA, Kram R. Effects of obesity and sex on the energetic cost and preferred speed of walking. *J Appl Physiol*. 2006; 100(2):390–398. [PubMed: 16210434]
5. Browning RC, Kram R. Effects of obesity on the biomechanics of walking at different speeds. *Med Sci Sports Exerc*. 2007; 39(9):1632–1641. [PubMed: 17805097]
6. Browning RC, Kram R. Energetic cost and preferred speed of walking in obese vs. normal weight women. *Obes. Res*. 2005; 13(5):891–899. [PubMed: 15919843]
7. Browning RC, McGowan CP, Kram R. Obesity does not increase external mechanical work per kilogram body mass during walking. *J Biomech*. 2009; 42(14):2273–2278. [PubMed: 19646701]
8. Browning RC, Modica JR, Kram R, Goswami A. The effects of adding mass to the legs on the energetics and biomechanics of walking. *Med Sci Sports Exerc*. 2007; 39(3):515–525. [PubMed: 17473778]
9. Browning RC, Reynolds MM, Board WJ, Walters KA, Reiser RF 2nd. Obesity does not impair walking economy across a range of speeds and grades. *J. Appl. Physiol*. 2013; 114(9):1125–1131. [PubMed: 23412900]
10. Buczek FL, Kepple TM, Siegel KL, Stanhope SJ. Translational and rotational joint power terms in a six degree-of-freedom model of the normal ankle complex. *J Biomech*. 1994; 27(12):1447–1457. [PubMed: 7806552]
11. Cavagna GA. Force platforms as ergometers. *J Appl Physiol*. 1975; 39(1):174–179. [PubMed: 1150585]
12. DeVita P, Helseth J, Hortobagyi T. Muscles do more positive than negative work in human locomotion. *J Exp Biol*. 2007; 210(19):3361–3373. [PubMed: 17872990]
13. DeVita P, Hortobágyi T. Obesity is not associated with increased knee joint torque and power during level walking. *J Biomech*. 2003; 36(9):1355–1362. [PubMed: 12893044]
13. Devita, P.; McNally, M.; Rider, P., et al. Proceedings of Annual Meeting of American Society of Biomechanics. Providence, RI: Brown University; 2010 Aug 18–21. Positive and negative muscle work in lean and obese adults during incline and decline walking; p. 2002010

15. Donelan JM, Kram R, Kuo AD. Mechanical work for step-to-step transitions is a major determinant of the metabolic cost of human walking. *J. Exp. Biol.* 2002; 205(Pt 23):3717–3727. [PubMed: 12409498]
16. Donelan JM, Kram R, Kuo AD. Simultaneous positive and negative external mechanical work in human walking. *J Biomech.* 2002; 35:117–124. [PubMed: 11747890]
17. Duncan JA, Kowalk DL, Vaughan CL. Six degree of freedom joint power in stair climbing. *Gait & Posture.* 1997; 5(3):204–210.
18. Geerligs M, Peters GWM, Ackermans PAJ, Oomens CWJ, Baaijens FPT. Linear viscoelastic behavior of subcutaneous adipose tissue. *Biorheology.* 2008; 45(6):677–688. [PubMed: 19065014]
19. Haight DJ, Lerner ZF, Board WJ, Browning RC. A comparison of slow, uphill and fast, level walking on lower extremity biomechanics and tibiofemoral joint loading in obese and nonobese adults. *J Orthop Res.* 2014; 32(2):324–330. [PubMed: 24127395]
20. Hills AP, Hennig EM, Byrne NM, Steele JR. The biomechanics of adiposity--structural and functional limitations of obesity and implications for movement. *Obes Rev.* 2002; 3(1):35–43. [PubMed: 12119658]
21. Hof AL. Scaling gait data to body size. *Gait & Posture.* 1996; 4(3):222–223.
22. Huang T-WP, Kuo AD. Mechanics and energetics of load carriage during human walking. *J Exp Biol.* 2013; 217:605–613. [PubMed: 24198268]
23. Hulens M, Vansant G, Lysens R, Claessens AL, Muls E, Brumagne S. Study of differences in peripheral muscle strength of lean versus obese women: an allometric approach. *Int. J. Obes. Relat. Metab. Disord.* 2001; 25(5):676–681. [PubMed: 11360150]
24. Karastergiou K, Smith SR, Greenberg AS, Fried SK. Sex differences in human adipose tissues - the biology of pear shape. *Biol Sex Differ.* 2012; 3:13. [PubMed: 22651247]
25. Kelly LA, Cresswell AG, Racinais S, Whiteley R, Lichtwark G. Intrinsic foot muscles have the capacity to control deformation of the longitudinal arch. *J R Soc Interface.* 2014; 11(93):20131188. [PubMed: 24478287]
26. Ker RF, Bennett MB, Alexander RM, Kester RC. Foot strike and the properties of the human heel pad. *Proc Inst Mech Eng H.* 1989; 203:191–196. [PubMed: 2701955]
27. Ker RF, Bennett MB, Bibby SR, Kester RC, Alexander RM. The spring in the arch of the human foot. *Nature.* 1987; 325:147–149. [PubMed: 3808070]
28. Kuo AD. Biophysics. Harvesting energy by improving the economy of human walking. *Science.* 2005; 309(5741):1686–1687. [PubMed: 16151001]
29. Kuo AD, Donelan JM, Ruina A. Energetic consequences of walking like an inverted pendulum: step-to-step transitions. *Exerc Sport Sci Rev.* 2005; 33(2):88–97. [PubMed: 15821430]
30. Lerner ZF, Board WJ, Browning RC. Effects of an obesity-specific marker set on estimated muscle and joint forces in walking. *Med Sci Sports Exerc.* 2014; 46(6):1261–1267. [PubMed: 24518193]
31. Lerner ZF, Board WJ, Browning RC. Effects of obesity on lower extremity muscle function during walking at two speeds. *Gait Posture.* 2014; 39(3):978–984. [PubMed: 24412270]
32. Liu W, Nigg BM. A mechanical model to determine the influence of masses and mass distribution on the impact force during running. *J Biomech.* 2000; 33:219–224. [PubMed: 10653036]
33. Pierrynowski MR, Winter DA, Norman RW. Metabolic measures to ascertain the optimal load to be carried by man. *Ergonomics.* 1981; 24(5):393–399. [PubMed: 7262062]
34. Pollock NK, Laing EM, Baile CA, Hamrick MW, Hall DB, Lewis RD. Is adiposity advantageous for bone strength? A peripheral quantitative computed tomography study in late adolescent females. *Am. J. Clin. Nutr.* 2007; 86(5):1530–1538. [PubMed: 17991669]
35. Rome LC, Flynn L, Goldman EM, Yoo TD. Generating electricity while walking with loads. *Science.* 2005; 309(5741):1725–1728. [PubMed: 16151012]
36. Runhaar J, Koes BW, Clockaerts S, Bierma-Zeinstra SMA. A systematic review on changed biomechanics of lower extremities in obese individuals: a possible role in development of osteoarthritis. *Obes Rev.* 2011; 12(12):1071–1082. [PubMed: 21812903]
37. Siegel KL, Kepple TM, Caldwell GE. Improved agreement of foot segmental power and rate of energy change during gait: inclusion of distal power terms and use of three-dimensional models. *J Biomech.* 1996; 29(6):823–827. [PubMed: 9147982]

38. Sloot LH, van der Krogt MM, Harlaar J. Energy exchange between subject and belt during treadmill walking. *J Biomech*. 2014; 47(6):1510–1513. [PubMed: 24589022]
39. Soule RG, Pandolf KB, Goldman RF. Energy expenditure of heavy load carriage. *Ergonomics*. 1978; 21(5):373–381. [PubMed: 668676]
40. Takahashi KZ, Kepple TM, Stanhope SJ. A unified deformable (UD) segment model for quantifying total power of anatomical and prosthetic below-knee structures during stance in gait. *J Biomech*. 2012; 45(15):2662–2667. [PubMed: 22939292]
41. Takahashi KZ, Stanhope SJ. Mechanical energy profiles of the combined ankle-foot system in normal gait: insights for prosthetic designs. *Gait Posture*. 2013; 38(4):818–823. [PubMed: 23628408]
42. Winter, DA. *Biomechanics and motor control of human movement*. Hoboken New Jersey: Wiley; 2009. p. 370
43. Zelik KE, Kuo AD. Human walking isn't all hard work: Evidence of soft tissue contributions to energy dissipation and return. *J Exp Biol*. 2010; 213(Pt 24):4257–4264. [PubMed: 21113007]
44. Zelik KE, Kuo AD. Mechanical work as an indirect measure of subjective costs influencing human movement. *PLoS ONE*. 2012; 7(2):e31143. [PubMed: 22383998]

Fig. 1.

Estimation of soft tissue contributions to walking. (A) Examples of soft tissues that may deform during walking. (B) Inverse dynamics yields joint powers assuming rigid bodies. Here six degree-of-freedom (rotation and translation) joint powers are computed. (C) Total mechanical work may be computed from COM work (performed through displacement of body center of mass, without rigid body assumptions) and peripheral work (for body motions relative to COM). Soft tissue work is estimated from the difference between inverse dynamics joint work and total mechanical work. Adapted from (43).

Fig. 2. Sagittal plane joint angle, torque, and power of the ankle, knee, and hip from inverse dynamics for non-obese (solid line) and obese (dotted line) participants ($N = 9$ and $N = 11$, respectively). Mean normalized values are shown, with shaded bands representing ± 1 standard deviation. All data were non-dimensionalized to account for differences in body size, using body mass, leg length, and gravitational acceleration as base units, with approximately equivalent dimensional scales shown on right-hand axes. Knee angle inset shows how flexion rate is lower for the obese group; dots indicate flexion amount and timing whose slope yield flexion rate 15% lower in obese ($p = 0.039$).

Fig. 3.

Work rates and joint powers over a stride for non-obese and obese participants (left and right columns, respectively) walking at 1.25 m/s. (A) Average COM and peripheral work rates, (B) Average joint powers for the ankle, knee, and hip, (C) Joint powers of ankle, knee, and hip, (D) Mechanical power measures including the total mechanical work rate (adding COM and peripheral work rates) and the summed joint powers, and (D) Soft tissue power, all normalized for body mass and leg length. Shown are means across participants with each shaded band denoting ± 1 standard deviation of variability. Stride is defined from heel strike to heel strike of one leg, and divided into phases (collision, rebound, preload, push-off,

swing) based on zero-crossings of COM work rate. Data are normalized using body mass, leg length, and gravitational acceleration as base units; approximate scale in units of W/kg is shown for reference.

Fig. 4.

Summary measures of normalized work for non-obese and obese participants, for each gait phase. (Top) Total mechanical work, and summed joint work (left/right bar pairs for each subject group, respectively), averaged across participants with error bars denoting 1 s.d.). Total mechanical work is defined as the integral of the sum of COM and peripheral work rates, and summed joint work as the integral of summed joint powers from ankle, knee, and hip; see Fig. 3). (Bottom) Soft tissue work, estimated from the difference between total mechanical power and summed joint power, integrated over each phase. Significant differences (*) were observed at collision ($p = 0.0004$) and push-off ($p = 0.0367$), with obese participants performing about 83% more negative soft tissue work during collision and 71% less at push-off. Normalized measures are shown, using body mass, leg length, and gravitational acceleration as base units.

Fig. 5. Mechanical work per stride performed by non-obese and obese groups (left and right bars of each pair, respectively), by type of work and by joint.). Work quantities include (A) COM, peripheral, summed joint, and soft tissue work per stride, as well as (B) work from ankle, knee, and hip, all normalized for body mass and leg length. Data shown are the positive and negative work (integrating intervals of positive or negative power; see Fig. 3), as well as the net work over a stride (dashed lines). Data shown are means across participants, with error bars denoting s.d. In relative terms, the obese group performed significantly more positive

and negative soft tissue work, but not net work. In terms of joint work, the obese group performed significantly different work only at the knee, with more positive work, less negative work, and more net work. Asterisks ‘*’ indicate statistically significant differences between groups $p < 0.05$.

Fig. 6.

Net metabolic rate (subtracting cost of standing and normalized by “unloaded body mass” and leg length) versus loaded body mass as a fraction of “unloaded body mass” for obesity (red, left labeled, dashed) and load carrying (blue, right labeled, solid) studies. To create a load carrying case with similar weight placement to the distribution of adipose tissue in the body of obese individuals, line 5 was created as a superposition of waist and thigh loading data from Browning et al. 2007. The ratio of waist-to-thigh weight added per unit of additional loaded mass uses the trunk-to-leg fat mass ratio from Browning et al. 2013. This

simulation shows a steeper slope than obesity studies lines 7 and 9 (6,9), suggesting that, on a mass-specific basis, walking while carrying soft fat tissue may be less metabolically costly than carrying attached solid weights.