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Abstract

Physical activity in children is important as it leads to healthy growth and physiological benefits. However, a cardiovascular health benefit can be partially negated by overloading in musculoskeletal tissues if there are excessive loads beyond the physiological range within the joints. To gain an initial understanding into this issue, the present study sought to compare joint loading between physiological effort-matched walking and cycling in children. With institutional ethical approval, 14 pre-pubertal children aged 8-12 walked on an instrumented treadmill and cycled on a stationary ergometer. Two methods were used to match physiological load. Cardiovascular loads between walking and cycling were matched using heart rate. Metabolic load was normalised by matching estimates of oxygen consumption. Joint reaction forces during cycling and walking as well as joint moments were derived using inverse dynamics. Peak compressive forces were greater on the knees and ankles during walking than during cycling. Peak shear peak forces at the knee and ankle were also significantly larger during walking than during cycling, independent of how physiological load was normalised. For both cycling conditions, ankle moments were significantly smaller during cycling than walking. No differences were found for knee moments. At equivalent physiological intensities, cycling results in less joint loading than walking. It can be speculated that for certain populations and under certain conditions cycling might be a more suitable mode of exercise than weight bearing activities to achieve a given metabolic load.

Keywords: JOINT LOADING, PAEDIATRIC OBESITY, PHYSICAL ACTIVITY, WEIGHT MANAGEMENT

Introduction

Physical activity (PA) is a key component for healthy growth in children. The current UK PA guidelines state that children should engage in at least 60 minutes of moderate to vigorous PA every day (Department of Health Physical Activity Health Improvement and Protection, 2011). Although following PA guidelines can protect children against cardiovascular diseases (Andersen et al., 2006) and overweight and obesity (de Bourdeaudhuij et al., 2013; Katzmarzyk et al., 2015; Ramires, Dumith, & Goncalves, 2015), evidence shows that the majority of children and adolescents are not meeting PA recommendations (Kalman et al., 2015). There has been a discussion in the literature regarding benefits of different PAs for children.

Children are advised to engage in weight bearing activities such as walking, jumping rope and hopscotch (Landry & Driscoll, 2012) as this can improve bone health (U.S. Department of Health and Human Services, 2008). Due to the fact that walking is a moderate intensity PA (Haskell et al., 2007; Landry & Driscoll, 2012; U.S. Department of Health and Human Services, 2008) that has been recommended for children (Lafortuna et al., 2010), incorporating it in children's daily activities seems to be an inexpensive and effective strategy for children to achieve PA recommendations. However, a recent study (Lerner et al., 2016) suggested that walking duration was related to increased loading on the medial knee compartment. Whilst a certain amount of loading on joints and bones is necessary for healthy bone development in children (Landry & Driscoll, 2012), excessive or increased physiological loading of the hip, knee and ankle joints, and increased plantar pressures during walking (Pau, Leban, Corona, Gioi, & Nussbaum, 2016) may be related to lower-limb and foot pain (Smith, Sumar, & Dixon, 2014; Stovitz, Pardee, Vazquez, Duval, & Schwimmer, 2008) and may act as a barrier to participation in PA (Smith et al., 2014). Thus, for certain populations which are more prone to lower limb injuries (e.g., children with excess body weight), non- bearing activities weight might more suitable activities to encourage PA engagement.

Additionally, cycling has been shown to be a protective factor against excess body weight (Bere, Seiler, Eikemo, Oenema, & Brug, 2011; Dudas & Crocetti, 2008), lead to good cardiorespiratory fitness (Maher, Voss, Ogunleye, Micklewright, & Sandercock, 2012; Oja et al., 2011), increase agility, balance, reaction response (Lirgg, Gorman, Merrie, & Hadadi, 2018; Rissel, Passmore, Mason, & Merom, 2013) and be an enjoyable activity for children (Chandler et al., 2015). However, although many benefits of cycling have been documented in the literature, no study has contrasted and documented joint loading characteristics between walking and cycling in children.

Understanding the differences in joint loading between these two activities will be a useful first step to differentiate PA recommendations in relation to paediatric populations of different characteristics in children. For example, those children who are more prone to lower limb injury or pain may be better advised to achieve their PA recommendations by means of non-weight bearing activities. Therefore, the purpose of this study was to investigate differences in joint loading between walking and cycling, but at similar physiological intensities in pre-pubertal children in order to compare activities that provide equivalent cardiovascular benefit.

Methods

Participants

With institutional ethical approval (reference number 0523-MHR-Jan/2016-1202), 17 pre-pubertal children (11 males) volunteered to participate in this study. The inclusion criteria were (1) to be aged 8-12 years and (2) to be able to cycle on a cycle ergometer and to walk on a treadmill; exclusion criteria were any physical impairment that prevented the practice of regular PA i.e. physical education classes or the practice of sports. The Physical Activity Readiness Questionnaire (PAR-Q) (Shephard, 1988) was used to assess any physical impairments or injuries in children. PA background of children was assessed using the validated (Kowalski, Crocker, & Faulkner, 1997) Physical Activity Questionnaire for Older Children (PAQ-C) (Crocker, Bailey, Faulkner, Kowalski, & McGrath, 1997). Written consent was obtained from parents in addition to written assent from children prior to their participation in the study.

Procedure

Participants were invited to attend the laboratory with their parents on one occasion. Data collection consisted of three different parts: 1) assessing anthropometric measurements of participants, 2) adjusting the stationary bicycle (Serotta International Cycling Institute, Boulder, CO, USA) according to the anthropometry of each child (see text below) and 3) the assessment of kinematics and kinetics during walking and cycling. Two methods were used to match physiological load. First, cardiovascular loads between walking and cycling were matched using heart rate (HR matched). A familiarization trial was performed on the treadmill and heart rate of children was obtained while they walked at a fast pace. Children were asked to walk on the treadmill as fast as they could. A submaximal test was performed on a cycle ergometer in order to match the physiological load achieved while walking on a treadmill.

Heart rate data were recorded using a validated (Giles, Draper, & Neil, 2016) V800 Polar heart rate monitor and a Polar H7 chest strap (Polar OY, Finland). During the second cycling trial the metabolic load between walking and cycling was normalised by matching oxygen consumption (VO_2 matched; equations are displayed below) using the following equations proposed by the American College of Sports Medicine (Glass & Dwyer, 2007). Subsequently, the equations were then readjusted to calculate equivalent work rate for children to perform another cycling trial.

Walking

VO_2 (ml.kg^{-1}.min^{-1}) = (0.1 x speed) + (1.8 x speed x grade) + 3.5

Cycling

VO_2 (ml.kg^{-1}.min^{-1}) = 1.8 x (work rate/mass in kg) + 3.5 + 3.5

Before each trial an acclimatisation period was used where participants had the chance to walk or cycle for at least five minutes. The acclimatisation period was ended once children were able to walk on a treadmill without holding the guard rails with their hands and verbally reported that they were walking comfortably on the equipment. For cycling, the acclimatisation period ended once the child was able to maintain a cycling pace of 65 revolutions per minute at a power output of 52 watts on a cycle ergometer and reported that they were comfortable with the equipment.

Anthropometrics

Stature was measured to the nearest 0.1 cm using a calibrated stadiometer (Charder HM200P Portstad Stadiometer) and body mass was assessed to the nearest 0.1 kg using a calibrated electronic weight scale (Seca, Hamburg, Germany). Standing height, sitting height and leg length were measured for assessing biological maturity. These variables are required to predict maturity offset according to predictive equations for boys and girls proposed by Mirwald et al. (2002). All participants were confirmed to be prepubertal. For adjusting the bicycle setup for each participant, measurements of inside leg, standing torso height, arm length and medial malleolus to first metatarsal were obtained using the FitKit Inseam Measurement Device (Fit Kit Systems, Montana, USA). Body mass index (BMI) was calculated as mass (in kg) divided by height (in m) squared.

Walking

Prior to the walking trials, participants practiced walking on an instrumented treadmill at a self-selected cadence. Subsequently, participants were asked to walk at their fastest walking speed on the treadmill. This walking trial started with a slow cadence and it was gradually increased to a point where the child would start running. Testing started once children reached their fastest walking cadence and lasted for approximately three minutes. Kinematic data were collected using a ten-camera three-dimensional motion capture system (Motion Analysis, Santa Rosa, CA, USA) at a sampling rate of 120 Hz. Ground reaction forces were measured simultaneously with force plates on a fully instrumented dual-belt treadmill at 960 Hz (Bertec Corp, Columbus, OH, USA). Thirty-one spherical retro-reflective markers were bilaterally positioned on surface anatomical landmarks of the lower limbs, trunk and head: first and fifth metatarsal head, lateral and medial malleoli, right and left calcanei, lateral and medial femoral epicondyles, the greater trochanters, base of sacrum, anterior superior iliac spines, at the distal end of each clavicle, c7, proximal sternum, right and left occipital bone landmarks, right and left orbital bone landmarks. Four additional markers were placed on thighs and shanks to identify these segments. .

Cycling

Participants performed two cycling trials and were instructed to maintain a pedalling rate of 65 revolutions per minute on a cycle ergometer. A metronome was set at 65 beats per minute to assist the participants in maintaining this target cadence. In addition, the cadence was closely monitored "online" by the experimenter, and instructions were given so children were aware when their pedalling rate was lower or higher than the one that was previously instructed. Equally to walking trials, each cycling trial lasted for approximately three minutes. Kinematic data were collected using a ten-camera three-dimensional motion capture system at a sampling rate of 120 Hz. Pedal reaction forces were collected at 960 Hz using a custom-made instrumented force pedal (model 9251AQ01, Kistler, Winterthur, Switzerland). Eleven spherical retro-reflective markers were bilaterally positioned on anatomical landmarks of the right leg: first and fifth metatarsal head, lateral and medial malleoli, calcanei, lateral and medial femoral epicondyles, the greater trochanters, anterior superior iliac spines. Two additional markers were placed on the right thigh and right shank to identify these segments. Prior to each cycling trial, participants familiarised themselves with the equipment and practiced cycling with the metronome. The order of the cycling trials, HR matched and VO_2 matched, was randomized. Each participant was fitted to the bike based on the recommendations of Grainger, Dodson, & Korff (2017).

Data analysis

Cycling trials were digitised with Cortex-64 3.6.1.1315 64-bit (Motion Analysis, Santa Rosa, CA, USA) and exported for further computations. Right-sided data, from walking and cycling trials, were selected for analysis. Kinematic cycling data were filtered using a 2nd order Butterworth low pass filter with a cut-off frequency of 10 Hz. Kinetic cycling data were filtered using a 2nd order Butterworth low pass filter with a cut-off frequency of 20 Hz. Joint Reaction forces and moments at the knee and ankle joints during cycling trials were estimated using inverse dynamics as described by Barratt, P.R. , Martin, J.C. , Elmer, S. J. & **Korff**, T. (2016).. All data from the cycling trials were analysed with a custom written script (MATLAB, Natick, MA, USA). The dependent variables considered to represent joint loading (Ericson & Nisell, 1986) were peak joint moments, shear (anterior-posterior) forces and compressive joint reaction forces at the knee and ankle joints. All dependent variables were average values across all available full revolutions.

For the walking trials, kinematic data were digitised and trimmed using Cortex. Kinetic data were filtered using a low pass fourth order Butterworth filter with a cut-off frequency of 6 Hz was used to remove noise (Shultz, D'Hondt, Fink, Lenoir, & Hills, 2014). All dependent variables relating to the walking trials were processed with Visual 3D software (C-Motion, Inc., Germantown, MD, USA) version 5. Reliability analyses were performed to obtain coefficients of variation. Ten consecutive gait cycles were used to calculate dependent variables from walking trials (Mills, Morrison, Lloyd, & Barrett, 2007; Neptune, Sasaki, & Kautz, 2008). From walking trials, dependent variables were calculated from right heel strike until right toe-off phase of each stride. Joint moments and reaction forces from cycling and walking trials calculated through inverse dynamics, were normalised by dividing by the participant's body mass. Time normalisations were computed for each stride and 101 points were exported to represent equal intervals from 0 to 100%.

Statistical analysis

The assessment of the normality of the data was performed using the Shapiro-Wilk test. Descriptive statistics were used to report the following variables: body mass, stature, BMI, age, PAQ-C score and the prediction of age of peak height velocity (biological maturity). To test the hypothesis that peak joint moments, peak shear and peak compressive forces would be different between walking and HR-matched cycling, a Hotelling's t-test was conducted. Another Hotelling's t-test was performed to test the hypothesis that peak joint moments, peak shear and peak compressive forces would be different between walking and VO2-matched cycling In case of significance post-hoc paired t-tests with a Bonferroni correction were conducted. Analyses were performed on the statistical software SPSS (Statistical Package for the Social Sciences Inc., Chicago, IL, USA), version 23.

Results

Descriptive characteristics of participants and overall results

Three participants failed to maintain 65 revolutions per minute during the HR matched cycling trial and five participants failed to maintain this pace during the VO_2 matched cycling trial. These participants cycled consistently faster than 65 revolutions per minute, so their cycling data were not compared to their walking trials. Table 1 presents participant characteristics. The mean PA score was 3.1, according to the PAQ-C. The prediction of the biological maturity of children was -2.2 years from the maximum velocity in stature growth during adolescence. The Hotelling's t-test for differences between HR matched walking and cycling was significant (F(9,5)=129.14, $p<0.001$). Similarly, results from the Hotelling's t-test testing the difference between VO_2 matched walking and cycling were also significant (F(9,2)=61.201, $p=0.016$).

Table 1. Participant characteristics.

	Mean	**SD**
Body mass (kg)	38.3	12.6
Stature (m)	1.43	0.1
BMI (kg/m^2)	18.3	3.1
Age (yr)	10.5	1.6
PAQ-C score (1 to 5)	3.1	0.7
APHV (yr)	-2.2	1.5

APHV: Prediction of Age of Peak Height Velocity

The mean and standard deviation (SD) walking speed achieved on the treadmill during walking trials was 1.43 metres per second (SD=0.3). The mean work rate achieved during cycling trials is described in table 2. Average work rate during the HR matched cycling trial was 46.0W (SD=15.9) and was 23.6W (SD=6.9) during the VO_2 matched cycling trial. Physiological demand values from the HR matched cycling trial was 126.6 beats per minute (SD=12.8) and was 12.1 ml.kg-1.min-1 (SD=1.6) from the VO_2 matched cycling trial.

Table 2. Description of average work rate from cycling trials (in watts).

	Cycling (heart rate matched)		**Cycling (VO2 matched)**	
	Mean	SD	Mean	SD
Work rate	46.0	15.9	23.6	6.9

n=14

Knee and ankle joint moments

Results revealed that ankle plantarflexion peak moments were greater during walking than during HR matched cycling (Table 3; $p<0.001$). Results also revealed that ankle plantarflexion peak moments were smaller during VO_2 matched cycling compared to walking (Table 4; $p<0.001$). There was no significant difference in knee extension and knee flexion moments between the cycling and walking ($p=0.616$ and $p=0.801$, respectively).

Table 3. Mean, standard deviation, peak moment (Nm/kg) and mean difference with 95% CI in peak moment between walking and cycling physiologically matched using HR.

	Walking		Cycling (heart rate matched)						
	Mean	**SD**	**Mean**	**SD**	**Mean difference**	**95% CI**	**t**	**df**	**p-value**
Knee extension	0.19	0.16	0.23	0.09	-0.024	(-0.13 to -0.08)	-0.51	13	0.616
Knee flexion	-0.17	0.05	-0.17	0.06	-0.006	(-0.05 to -0.04)	-0.26	13	0.801
Ankle plantarflexion	1.14	0.24	0.35	0.09	0.803	(0.64 to 0.97)	10.50	13	**<0.001**

Using the heart rate equation to match phhysiological demands from walking trials n=14

Table 4. Mean, standard deviation, peak moment (Nm/kg) and mean difference with 95% CI in peak moment between walking and cycling physiologically matched using VO_2.

	Walking		Cycling (VO_2 matched)						
	Mean	**SD**	**Mean**	**SD**	**Mean difference**	**95% CI**	**t**	**df**	**p-value**
Knee extension	0.19	0.16	0.14	0.13	0.056	(-0.09 to 0.20)	0.87	11	0.405
Knee flexion	-0.17	0.05	-0.16	0.09	-0.021	(-0.08 to 0.04)	-0.79	11	0.444
Ankle plantarflexion	1.14	0.24	0.31	0.11	0.862	(0.70 to 1.04)	10.86	11	**<0.001**

Using American College of Sports Medicine equations n=12

Knee and ankle shear forces

Table 5 shows peak anterior and posterior shear forces on knees and ankles during walking and HR matched cycling. Shear peak anterior forces at the knee and ankle were significantly greater during walking than during cycling ($p<0.001$). Similarly, shear peak posterior forces at the knee and ankle were greater during walking than during cycling ($p<0.001$).

Table 5. Mean, standard deviation, peak shear force (N/kg) and mean difference with 95% CI in peak moment between walking and cycling physiologically matched using HR.

	Walking		Cycling (heart rate matched)						
	Mean	**SD**	**Mean**	**SD**	**Mean difference**	**95% CI**	**t**	**df**	**p-value**
Knee anterior	1.12	0.37	0.63	0.27	0.576	(0.31 to 0.85)	4.60	13	**<0.001**
Knee posterior	-1.39	0.41	-0.70	0.30	-0.709	(-1.04 to -0.39)	-4.71	13	**<0.001**
Ankle anterior	1.59	0.34	0.80	0.27	0.869	(0.64 to 1.09)	8.37	13	**<0.001**
Ankle posterior	-1.77	0.49	-0.80	0.31	-0.980	(-1.37 to -0.59)	-5.37	13	**<0.001**

Using the heart rate equation to match phhysiological demands from walking trials n=14

Peak anterior and posterior shear forces on knees and ankles were also greater during walking than in VO_2 matched cycling. Table 6 shows that shear peak anterior forces for VO_2 matched cycling were lower at knee and at the ankle than during walking ($p<0.001$). Shear peak posterior forces during VO_2 matched cycling were also lower, at the knee and ankle ($p<0.001$), than during walking.

Table 6. Mean, standard deviation, peak shear force (N/kg) and mean difference with 95% CI in peak moment between walking and cycling physiologically matched using VO_2.

	Walking		Cycling (VO_2 matched)						
	Mean	**SD**	**Mean**	**SD**	**Mean difference**	**95% CI**	**t**	**df**	**p-value**
Knee anterior	1.12	0.37	0.32	0.21	0.820	(0.48 to 1.16)	5.34	11	**<0.001**
Knee posterior	-1.39	0.41	-0.77	0.27	-0.688	(-1.05 to -0.33)	-4.25	11	**0.001**
Ankle anterior	1.59	0.34	0.50	0.27	1.092	(0.77 to 1.42)	7.25	11	**<0.001**
Ankle posterior	-1.77	0.49	-0.87	0.29	-1.011	(-1.43 to -0.59)	-5.32	11	**<0.001**

Using American College of Sports Medicine equations n=12

Knee and ankle compressive forces

Table 7 describes compressive peak forces on the knees and ankles of children during walking and HR matched and VO_2 matched cycling trials. Results revealed that compressive peak forces were greater on the knees and ankles during walking than during cycling ($p = <0.001$). Compressive peak forces in the knees and ankles were significantly larger in walking than during VO_2 matched cycling ($p = <0.001$).

Table 7. Mean, standard deviation, peak compressive force (N/kg) and mean difference with 95% CI in peak moment between walking and cycling.

	Walking		Cycling (heart rate matched)						
	Mean	**SD**	**Mean**	**SD**	**Mean difference**	**95% CI**	**t**	**df**	**p-value**
Knee	-11.94	1.79	-3.33	0.99	-8.859	(-9.84 to -7.88)	-19.59	13	**<0.001**
Ankle	-12.70	1.74	-3.90	1.01	-9.038	(-9.95 to -8.13)	-21.43	13	**<0.001**
	Walking		**Cycling (VO_2 matched)**						
Knee	-11.94	1.79	-2.61	0.71	-9.474	(-10.79 to -8.16)	-15.85	11	**<0.001**
Ankle	-12.70	1.74	-3.24	0.93	-9.575	(-10.96 to -8.19)	-15.26	11	**<0.001**

Using American College of Sports Medicine equations n=12. Using the heart rate equation to match physiological demands from walking trials n=14

Discussion

The purpose of this study was to compare joint loading between walking and cycling in children. To quantify joint loading, we computed joint moments and shear and compressive joint reaction forces during both activities. We found that during cycling ankle moments as well as shear and compressive forces in knee and ankle joints were smaller compared to walking independent of how physiological load was matched between the two tasks. The present results thereby contribute important information to the body of knowledge relating to PA and the associated physiological and mechanical loads of walking and cycling in children.

Children are advised to engage in at least 60 minutes of moderate to vigorous PA every day (Department of Health Physical Activity Health Improvement and Protection, 2011). This recommendation includes a wide range of PA including vigorous activities and activities that strengthen muscles and bones (Department of Health Physical Activity Health Improvement and Protection, 2011). Specifically, engaging in recommended PA types and levels can lead to a number of physiological benefits such as improved cardiometabolic fitness, body composition and bone health (Landry & Driscoll, 2012).

Weight bearing physical activities such walking are advised for children, as they can improve bone health (U.S. Department of Health and Human Services, 2008). Walking is a moderate intensity task (Haskell et al., 2007; Landry & Driscoll, 2012; U.S. Department of Health and Human Services, 2008) has been recommended for children and adolescents (Lafortuna et al., 2010) to facilitate physiological benefits. For children with healthy weight, walking is a suitable activity to achieve physiological benefits (Landry & Driscoll, 2012) and when combined with other activities such as skipping or jumping, for can provide an instance, adequate stimulus for healthy bone development (Landry & Driscoll, 2012).

Whilst a certain amount of joint and bone loading is beneficial for health bone development as it can contribute to optimising bone mass in children (Landry & Driscoll, 2012), there may also be situations in which excessive or increased physiological forces in the joints can lead to pain and injury. In this case, cycling might be an alternative option for PA as it can evoke similar physiological benefits in children, such as protecting against excess body fat (Bere et al., 2011), leading to good cardiorespiratory fitness (Maher et al., 2012) and increasing physical abilities such as agility, balance and reaction response (Lirgg et al., 2018).

Thus, in situations where there is a predisposition for joint overloading, pain or injury, non-weight bearing tasks might be a more suitable mode of exercise to achieve similar physiological benefits, whilst reducing the risk for injury. Ericson & Nisell, (1986), for example, argued that lower tibiofemoral forces during cycling compared to weight bearing activities might make cycling a more appropriate rehabilitative activity for patients recovering from surgery. Similarly, Lerner et al. (2016) suggested that walking duration and obesity were related to increased loading on the medial knee compartment. Pau et al. (2016) documented that walking in association with excess body weight and backpack carriage can considerably increase peak plantar pressure in a way that can cause damage to the foot structure. Evidence shows that meniscal injuries can affect children early in childhood (Millett, Willis, & Warren, 2002; Stanitski, Harvell, & Fu, 1993).

Findings from this study demonstrate that at similar physiological loads, joint loading during cycling is less than during walking. These results let us speculate that in certain paediatric clinical population such as children with overweight/obesity or a predisposition for joint abnormalities, cycling may result in less joint pain and thereby reduce barriers to PA. This in turn could have implications for PA recommendations for such populations (e.g., weight management programmes). A limitation to this speculation is that this study only investigated healthy weight children. However, it is likely that a study with overweight participants would show similar if not exaggerated results. In the present study, the external load was adjusted using a fast walking pace as a reference for cycling trials. Thus, it is unknown whether the magnitude of the results could have been different if children were asked to perform HR matched and/or VO2 matched cycling trials and use these tasks as work load references for walking trials. In order to confirm joint loading magnitude differences between walking and cycling further studies should investigate forces and moments using external loads from cycling as a reference for walking. Another limitation of this study was that the joint reaction forces derived from inverse dynamics do not consider individual muscle forces or antagonistic contraction surrounding ankle and knee joints.

Thus, further research should specifically investigate the benefits of non-weight bearing activities in those populations that are predisposed to joint injuries taking individual muscle contributions into consideration. Our results provide a useful basis for future research to assess these speculative links explicitly, specifically with respect to overweight and obese children.

Conflict of interest statement

The authors have no conflicts of interest.

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