Published by Oxford University Press on behalf of the International Epidemiological Association *International Journal of Epidemiology* 2012;**41**:1124–1131
 Advance Access publication 9 May 2012 doi:10.1093/ije/dys073

High impact activity is related to lean but not fat mass: findings from a population-based study in adolescents

Kevin Deere,[1] Adrian Sayers,[1,2] George Davey Smith,[2,3] Jörn Rittweger[4] and Jon H Tobias[1]*

[1]Musculoskeletal Research Unit, School of Clinical Sciences, University of Bristol, Bristol, UK, [2]School of Social and Community Medicine, University of Bristol, Bristol, UK, [3]Medical Research Council Centre for Causal Analyses in Translational Epidemiology, University of Bristol, Bristol, UK and [4]Division Space Physiology, Institute of Aerospace Medicine, German Aerospace Center, Cologne, Germany

*Corresponding author. Avon Orthopaedic Centre, Southmead Hospital, Bristol BS10 5NB, UK. E-mail: Jon.Tobias@bristol.ac.uk

Accepted 3 April 2012

Background Objective measures of physical activity calibrated against energy expenditure may have limited utility in studying relationships with musculoskeletal phenotypes. We wished to assess an alternative approach using an accelerometer calibrated according to impact loading.

Methods Of the 17-year olds from the Avon Longitudinal Study of Parents and Children (ALSPAC), 732 wore Newtest accelerometers while performing day-to-day activities for a mean of 5.8 days. Outputs were categorized as light, moderate, high and very high impact, based on the thresholds identified in 22 adolescents during graded activities. In subsequent regression analyses, activity data and fat mass were normalized by log transformation.

Results The number of counts relating to high impact activity was ~2% that of light impact activity, and 33% greater in boys when compared with girls. High impact activity was more strongly related to lean mass [light: 0.033 (95% CI −0.023 to 0.089), moderate: 0.035 (95% CI −0.010 to 0.080) and high: 0.044 (95% CI 0.010 to 0.078)] (β = SD change in outcome per doubling in activity, height adjusted, boys and girls combined). In contrast, lower impact activity was more strongly related to fat mass [light: −0.069 (95% CI −0.127 to −0.011), moderate: −0.060 (95% CI −0.107 to −0.014) and high: −0.033 (95% CI −0.069 to 0.003)]. In a more fully adjusted model including other activity types and fat/lean mass, lean mass was related to only high activity (boys and girls combined), whereas fat mass was related to only moderate activity (girls only).

Conclusions Using an accelerometer calibrated according to impact loading revealed that high impact activity is related to lean but not fat mass.

Keywords Accelerometer, fat mass, lean mass, ALSPAC, impact loading

Introduction

Objective measures of physical activity (PA) are widely used in epidemiological studies, since questionnaires providing information about day-to-day PA and exercise may be unreliable, particularly when applied to child populations.[1] For example, an Actigraph device has been employed in the Avon Longitudinal Study of Parents and Children (ALSPAC) to study relationships between PA and childhood obesity, for which it is well suited; results can be extrapolated to beyond the period when worn,[2] and the output is calibrated in terms of energy expenditure[3] and strongly related to fat mass.[4] Using this approach, PA has been defined as light, moderate or vigorous, based on the thresholds of 3600 and 6200 cpm, reflecting the transition from normal to brisk walking, and brisk walking to jogging, respectively.[3] In our recent study, we found that vigorous activity is more strongly related to fat mass compared with less intense activity.[5]

Acceleration sensors have also been used to examine relationships between PA and musculoskeletal phenotypes, based on the accelerations along the vertical axis, which provide a measure of skeletal loading. Such research has relevance for other important health outcomes, particularly those related to ageing, such as sarcopenia and osteoporosis. This approach has been fruitful, demonstrating that habitual PA is positively related to lean mass,[5,6] bone mass[5–8] and other measures of bone strength.[9–11]

The Actigraph output, comprising number of counts over a given time frame, integrates both frequency and magnitude of acceleration events, making it impossible to separate out exposure to accelerations according to their magnitude. This limited information about exposure to specific accelerations is compounded by the fact that accelerations beyond 2.5 g above gravitational force (where 1 g = earth's gravitational force) are filtered out. Based on a previous study in premenopausal women, whereas activities such as walking (0.3–1.0 g) and stepping (1.1–2.4 g) generate g-forces below this threshold, jogging (2.5–3.8 g), running (3.9–5.3 g) and jumping (5.4–9.2 g) produce considerably higher forces.[12] This inability of the Actigraph to detect exposure to rare high magnitude accelerations limits analysis of relationships between habitual PA and musculoskeletal outcomes such as bone strength, since the latter primarily responds to the small proportion of relatively high magnitude forces and impacts. For example, laboratory studies demonstrate a strong dose–response between mechanical strain and bone formation and resorption,[13,14] and a recent meta-analysis found that exercise regimens that produce impact loading are associated with greater bone mineral density (BMD) levels and thus bone strength.[15]

The newer generation of accelerometers record vertical accelerations across a wide range of predetermined g-bands, with the number of counts representing the number of acceleration events of a specific magnitude, allowing exposure to rare high impact events to be separately recorded. For example, in an exercise intervention study, increments in femoral neck BMD were related to counts of vertical accelerations related to high impacts, as assessed in 64 premenopausal women wearing a Newtest device (Newtest Oy, Oulu, Finland).[12] In the present study, we examined whether such an approach might prove accurate in evaluating PA in relation to musculoskeletal and adiposity outcomes in a population-based setting. Specifically, we wished to determine whether, having used a Newtest device to partition physical activity exposure into light, moderate and high impact bands, musculoskeletal outcomes like lean mass show a stronger association with high impact activity, when compared with fat mass where the relationship with PA is largely governed by calorie consumption.

Methods

Study participants

ALSPAC is a geographically based birth cohort study investigating factors influencing health, growth and development of children. All pregnant women residents within a defined part of the former county of Avon in South West England with an expected date of delivery between April 1991 and December 1992 were eligible for recruitment, of whom 14 541 were enrolled[16] (http://www.alspac.bristol.ac.uk). Ethical approval was obtained from the ALSPAC Law and Ethics committee and relevant local ethics committees. Written informed consent was provided by all parents and young people provided written assent. Data were collected by self-completion postal questionnaires sent to parents by linkage to computerized records, abstraction from medical records and from examination of the children at research clinics.

Newtest accelerometer measurements in ALSPAC

The present study was based on the research clinic held for those at ~17 years of age, between December 2008 and June 2011, to which all ALSPAC members were invited. Those who agreed to wear an accelerometer were fitted with a version of the Newtest monitor produced for this study. This uniaxial device recorded the number of accelerations within 33 separate bands across the range of 0.3–9.9 g above gravitational force (1 g), over the period the monitor was worn, as previously described for other research applications.[12] Each single acceleration measured in any band is recorded as a single count. Participants were asked to wear it for seven consecutive days during waking hours and take it off only at times when it might get wet or for contact sports. Participants were asked to record a diary when the monitor was worn, a valid recording being defined as a minimum of 8 h recording per day for 2 days. Since the monitor did not have an internal clock, we used number of days the monitor was worn, based on diaries, as the denominator when calculating number of counts/day.

Other data

Data on lean and fat mass were obtained from total body DXA scans performed on a Lunar Prodigy at the same clinic visit. Height was measured using a Harpenden stadiometer (Holtain Ltd., Crymych, UK). Maternal social class was derived from a self-report questionnaire at 32 weeks' gestation.

Classification of output from the Newtest accelerometer

To enable counts in different g-bands to be partitioned according to intensity, we recorded the output of the Newtest during a range of supervised activities in a separate group of schoolchildren. After providing informed consent, 22 children uninvolved in ALSPAC were asked to wear both Newtest and GT1M Actigraph devices. Participants were recorded during sitting (3 min), normal walking, brisk walking, jogging/running and jumping. Participants completed four laps around an indoor jogging track (118.4 m) at a steady pace for normal walking (mean 4.7 km/h), brisk walking (mean 6.2 km/h) and jogging/running (mean 11.3 km/h). For the jumping activity, participants performed repeated two-footed jumps off a 38 cm high ledge for 3 min.

Statistical methods

Raw data from both activity monitors was read into STATA 11.2 MP (College Station, TX, USA) using custom-designed code. Thresholds identified above were applied to the Newtest output and median (+interquartile range) number of light/moderate/high impact counts per subject was subsequently calculated, expressed as number of counts/day across each impact band. Separate regressions were used to assess the relationship between activity counts and fat mass and lean mass, which were adjusted for height + maternal social class. For regression analyses, fat mass and activity data were normalized by log transformation. Further models were examined in which fat mass was adjusted for lean mass and vice versa, and activity adjusted for that in adjacent bands.

Results

Participant characteristics

Of the 5084 adolescents attending the ALSPAC research clinic at the age of 17 years, 3925 were asked if they would wear an accelerometer, of whom 2472 agreed; the monitor was available for 1390 participants (Figure 1). Of the 1175 subjects who returned

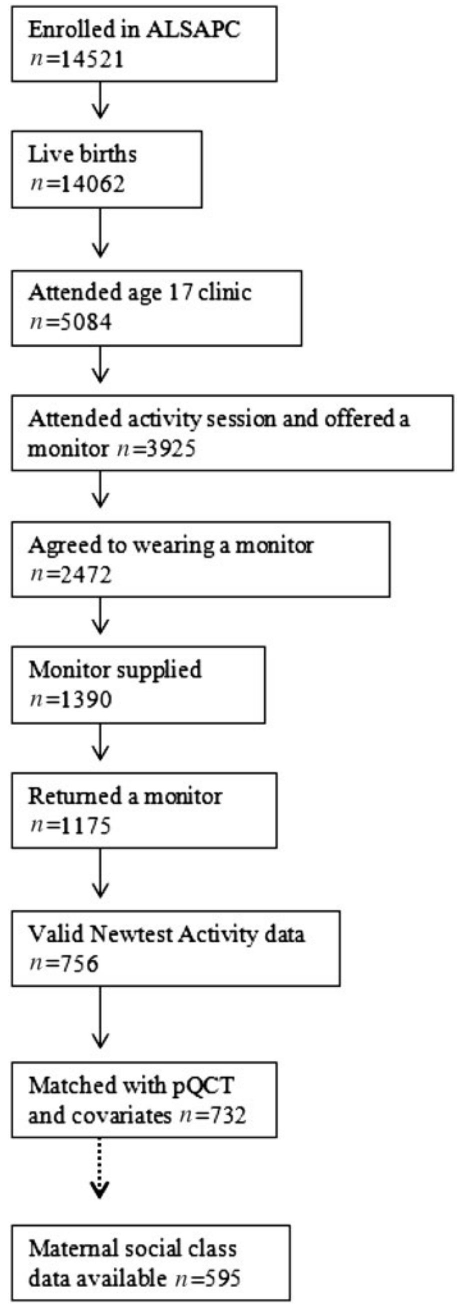

Figure 1 Flow diagram showing the participant *n* at each stage of the data preparation

the monitor, this was damaged or non-functional in 22 cases, returned unworn in 189 cases and returned either without a completed diary or with a diary indicating that it had been worn for <8 h/day for 2 days ($n = 232$). This left 756 participants with valid recordings, of whom 732 (295 boys) had information about covariates, with a mean age of 17.7 years (Table 1). Accelerometers were worn for a mean of 5.8 days. As expected, boys were taller and had greater lean mass, whereas fat mass was higher in girls. Those included in this study had a higher socio-economic status

Table 1 Descriptive statistics

Variable	Sex	Mean (SD)	Median	25th percentile	75th percentile
Continuous data					
Age (years)	M	17.7 (0.3)	–	–	–
	F	17.7 (0.3)	–	–	–
	All	17.7 (0.3)	–	–	–
Total days	M	5.9 (1.3)	–	–	–
	F	5.8 (1.4)	–	–	–
	All	5.8 (1.4)	–	–	–
Height (cm)	M	178.7 (6.9)	–	–	–
	F	164.8 (5.7)	–	–	–
	All	170.4 (9.2)	–	–	–
Weight (kg)	M	71.5 (13.1)	–	–	–
	F	63.1 (11.6)	–	–	–
	All	66.5 (12.9)	–	–	–
Lean mass (kg)	M	54.8 (5.9)	–	–	–
	F	38.0 (4.0)	–	–	–
	All	44.8 (9.5)	–	–	–
Fat mass (kg)	M	13.4 (9.5)	10.2	6.9	17.1
	F	21.6 (9.1)	19.8	15.1	25.6
	All	18.3 (10.1)	16.6	10.7	23.3
Light counts	M	4558.0 (3709.2)	3626.4	2083.6	5818.3
	F	3748.3 (2517.0)	3122.8	1978.7	4779.8
	All	4074.6 (3077.4)	3277.3	1981.1	5177.7
Moderate counts	M	1245.4 (1335.4)	841.4	457.0	1551.3
	F	952.5 (848.7)	707.1	372.6	1251.5
	All	1070.6 (1080.5)	740.4	412.5	1359.2
High counts	M	96.8 (146.1)	46.6	23.6	96.2
	F	72.6 (128.9)	34.9	15.4	74.1
	All	82.3 (136.5)	38.9	18.3	82.4
Categorical data		**Boys, *n* (%)**	**Girls, *n* (%)**		
Maternal social class	I	23 (9.2)	30 (8.7)		
	II	91 (36.6)	122 (35.3)		
	III[a]	109 (43.8)	144 (41.6)		
	III[b]	14 (5.6)	14 (4.1)		
	IV	10 (4.0)	30 (8.7)		
	V	2 (0.8)	6 (1.7)		

Characteristics of 732 ALSPAC participants in the accelerometer study (295 boys, 437 girls).
Social class data $n = 595$. [a]Non-manual, [b]manual.
Light counts 0.5–1.1 g; moderate 1.1–3.1 g; high >3.1 g.

(assessed by maternal social class) than the original (data not shown).

Classification of outputs from the Newtest accelerometer

In the classification study, 22 local schoolchildren uninvolved with ALSPAC (mean age 17.1 years, 15 boys) participated (Table 2). In contrast to normal walking, brisk walking (i.e. moderate impact) was associated with an increase in counts within bands >1 g, whereas jogging/running (i.e. high impact) led to an increase in counts within bands >2 g (Figure 2). Jumping (i.e. very high impact) was associated with a biphasic pattern, namely an increase in counts within bands <2 and >5 g (of which the former presumably reflected climbing to the top of the step before the actual jump took place). The Newtest output was subsequently categorized into sedentary (0.3–0.5 g), light (0.5–1.1 g), moderate (1.1–3.1 g) and high (>3.1 g) impact activity.

Table 2 Descriptive statistics of the substudies

Characteristic	Non-ALSPAC substudy	
	Sex	Mean (SD)
Age (years)	M	17.2 (0.5)
	F	16.9 (0.4)
	All	17.1 (0.5)
Height (cm)	M	177.8 (5.2)
	F	167.5 (8.0)
	All	174.9 (7.6)
Weight (kg)	M	71.4 (8.1)
	F	53.8 (7.1)
	All	66.4 (11.2)

$n = 22$ (boys = 15, girls = 7).

PA in ALSPAC

Classifying activity in this way, the median number of counts accrued per day in the 732 ALSPAC participants (Table 1). There was a profound fall in number of counts on moving from lower to higher impact activity. For example, the number of counts relating to high band activity was ~2% of that relating to light activity. The extent of activity recorded within any given impact band was strongly related to that in adjacent impact bands, as reflected by $r = 0.78$ and $r = 0.75$ for the correlations between light vs moderate and moderate vs high impacts, respectively.

PA vs lean mass

Light impact activity was not related to lean mass. However, a positive relationship was observed with higher impact activity, with a progressive increase in β-coefficients in analyses based on boys and girls combined, on moving from light through to high (Table 3). Although regression coefficients were generally higher in girls, formal gender interaction tests were all $P > 0.1$. Similar results were obtained after adjusting for socio-economic positions

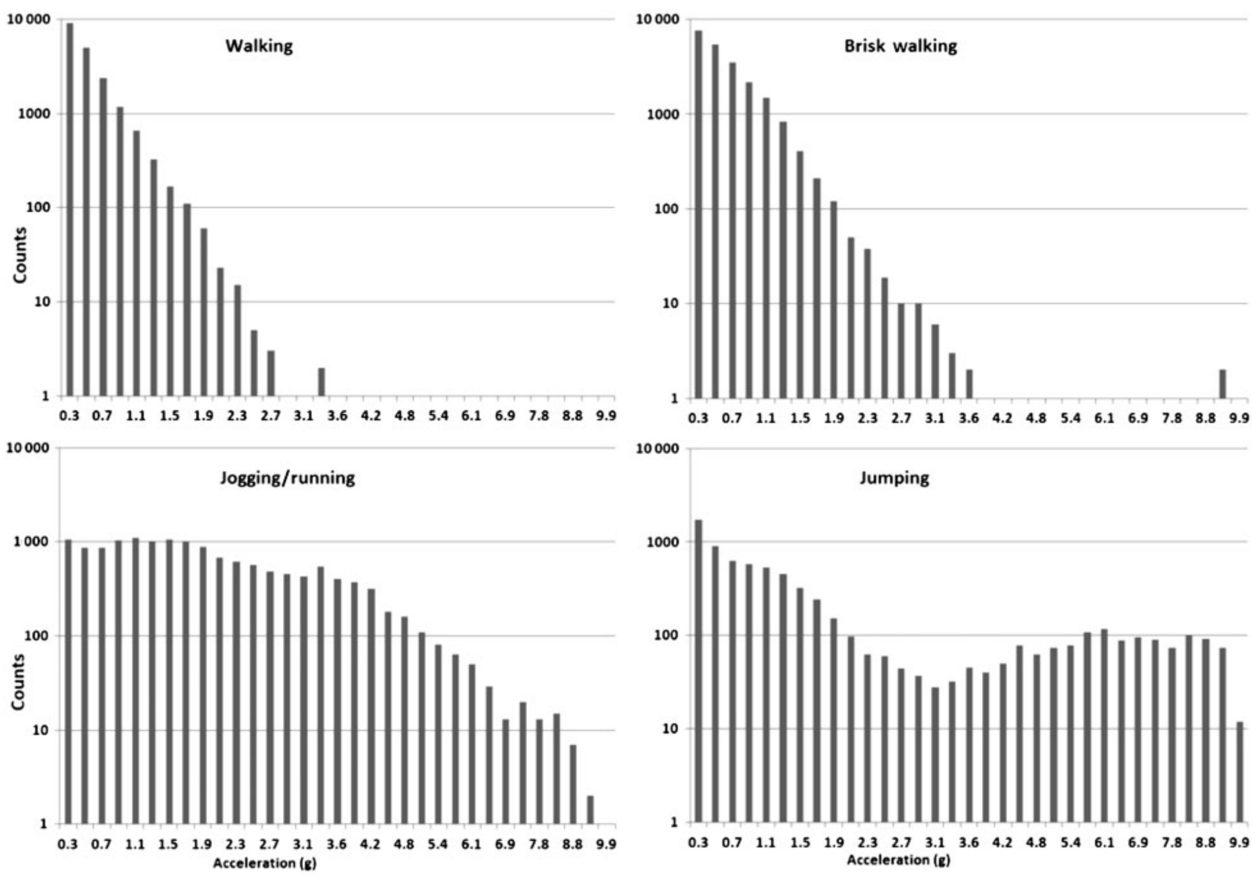

Figure 2 Impact profile of 15 boys and 7 girls undergoing a range of different supervised activities as shown. Each bar represents the sum of counts accrued within that g-band for all subjects combined on a logarithmic scale

Table 3 Analyses between body composition and g-bands in two models

Outcome	g-Band	Sex	Minimally adjusted coefficient (95% CI)	Fully adjusted coefficient (95% CI)
Fat mass	Light	M	−0.027 (−0.121 to 0.067)	−0.110 (−0.278 to 0.059)
		F	−0.075 (−0.131 to −0.019)	−0.006 (−0.089 to 0.077)
		All	−0.069 (−0.127 to −0.011)	−0.024 (−0.119 to 0.071)
	Moderate	M	0.008 (−0.075 to 0.091)	0.107 (−0.101 to 0.315)
		F	−0.077 (−0.119 to −0.035)	−0.069 (−0.151 to 0.013)
		All	−0.060 (−0.107 to −0.014)	−0.048 (−0.150 to 0.054)
	High	M	0.010 (−0.053 to 0.074)	0.000 (−0.092 to 0.091)
		F	−0.038 (−0.071 to −0.005)	−0.016 (−0.058 to 0.026)
		All	−0.033 (−0.069 to 0.003)	0.008 (−0.042 to 0.058)
Lean mass	Light	M	−0.006 (−0.078 to 0.067)	0.036 (−0.095 to 0.167)
		F	0.020 (−0.028 to 0.069)	0.035 (−0.036 to 0.107)
		All	0.033 (−0.023 to 0.089)	0.024 (−0.067 to 0.115)
	Moderate	M	−0.005 (−0.069 to 0.058)	−0.072 (−0.234 to 0.089)
		F	0.015 (−0.021 to 0.052)	−0.032 (−0.103 to 0.038)
		All	0.035 (−0.010 to 0.080)	−0.045 (−0.143 to 0.053)
	High	M	0.009 (−0.040 to 0.058)	0.047 (−0.023 to 0.117)
		F	0.033 (0.005 to 0.061)	0.045 (0.009 to 0.080)
		All	0.044 (0.010 to 0.078)	0.055 (0.007 to 0.102)

Associations between counts per day according to impact band and fat and lean mass in 732 participants (295 boys, 437 girls). Minimally adjusted model adjusted for height. Fully adjusted model additionally adjusted for activity in other bands, and fat/lean mass. Coefficients show percentage change in fat mass per percentage change in activity and SD change in lean mass per doubling in activity. Light 0.5–1.1 g; moderate 1.1–3.1 g; high >3.1 g. Minimally adjusted model: for associations with lean mass, gender interaction tests were all $P > 0.1$. For associations with fat mass, there was evidence of a gender interaction in the case of moderate and high impact activity ($P = 0.005$, $P = 0.04$, respectively). Fully adjusted model: for lean mass, formal gender interaction tests for light impact was $P > 0.1$, whereas moderate and high impact activity were $P = 0.05$. In the case of fat mass, there was evidence of a gender interaction for moderate and high impact activity ($P = 0.001$, $P = 0.01$, respectively), but not for light-impact activity ($P = 0.13$).

(our unpublished findings). We examined a further model adjusted for height, fat mass and other activity bands. There was a positive relationship between lean mass and high impact activity in girls and in boys and girls combined, whereas no independent association was observed with light or moderate impact activity (Table 3).

PA vs fat mass

Light, moderate and high impact activities were inversely related to fat mass in our minimally adjusted model (Table 3). These relationships became weaker on moving from light to moderate to high impact activity, as reflected by decreasing beta coefficients. The inverse association between PA and fat mass was largely restricted to girls, with evidence of a gender interaction in the case of moderate and high impact activity ($P = 0.005$ and $P = 0.04$, respectively). Similar results were obtained after adjusting for socio-economic positions (our unpublished findings). In a further model adjusted for height, lean mass and other activity bands, an inverse association was observed between fat mass and moderate impact activity in girls ($P = 0.001$ for gender interaction), whereas there was no association with light or high impact activity (Table 3).

Discussion

To our knowledge, this represents the first study to evaluate PA according to the degree of impact in a population-based setting. Based on a sample of 732 adolescents, we found that only a small proportion of activity comprised high impacts (~2% that of light impacts), and that more boys participated in high impact activity than girls, consistent with descriptions of vigorous PA as characterized by the Actigraph.[5] However, in contrast to results of the latter study, PA appeared to show a distinct relationship with fat and lean mass, since lean mass was more strongly related to higher impact activity, whereas fat mass was more strongly related to lower impact activity. In spite of this apparent difference compared with use of the Actigraph, there was surprisingly good agreement between Newtest and Actigraph outputs as recorded in a small number of ALSPAC participants (our unpublished observations).

Our observation that the relationship between PA and lean mass is greatest for higher impact activities is consistent with the fact that activities such as jumping are closely related to muscle strength.[17] This would appear to represent a distinction from fat mass, which was more strongly related to low and moderate impact activity, suggesting that use of the Newtest accelerometer enables relationships between PA and fat mass to be distinguished from those with musculoskeletal phenotypes. This conclusion was supported by findings from models adjusted for other activity types, in which a positive relationship with lean mass was only observed for high impact activity, whereas an inverse association with fat mass was only seen for moderate activity (confined to girls). However, due to strong correlations between adjacent activity bands, the apparent disappearance of effects may in part have been due to issues related to colinearity such as variance inflation and the spreading of the effects across correlated predictors with different measurement error properties.

One implication of our results is that although effective at reducing obesity, current recommendations to promote PA by targeting low impact activity like walking[18] may have little effect on the musculoskeletal system, which may require exposure to higher impacts resulting from activities such as jogging, running or jumping. For example, based on our fully adjusted model, moving from the 25th to 75th centile of high impact activity is predicted to lead to a 0.1 SD increase in total body lean mass. Our findings may have particular relevance to skeletal development, optimization of which may be important in reducing the risk of osteoporosis in later life.[19] Although the present study was limited to analysing lean mass, we plan to extend our analyses to examine relationships with other musculoskeletal phenotypes available in ALSPAC, including hip DXA and tibial pQCT scans.

The inverse association that we found between PA and fat mass is consistent with previous observations based on Actigraph data.[4] However, the present observation that medium impact activity was inversely related to fat mass in girls, whereas no association was seen for high impact activity in fully adjusted analyses, contrasts with findings from our previous study based on the same cohort at the age of 15 years, where the relationship between fat mass and activity as assessed by Actigraph was predominantly with the extent of vigorous activity.[5] This difference may in part reflect the differences in signal conditioning between the Actigraph (low-pass filtered counts) and the Newtest device (full spectrum), as exemplified by activities such as jogging, which will largely be captured within the >6200 cpm band as used to define vigorous intensity on the Actigraph, whereas many of the counts accrued by the Newtest device will be in the moderate impact band (Figure 2). The present results also differ from our previous findings in that fat mass was most strongly related to activity in females. This may have reflected a combination of lower statistical power in males due to smaller numbers, particularly for analyses involving adjustment for multiple factors.

Limitations

Participants were not necessarily representative of the population as a whole. Evidence that participants were of higher social class than other ALSPAC members who did not participate is consistent with this view. The fact that we were unable to measure PA during activities such as contact sports when accelerometers need to be removed applies to other studies of this type, including our previous investigations based on the Actigraph. One particular limitation is the reliance on accurate use of the timesheet (for measurement of time worn) owing to the lack of an internal clock in the Newtest device. A further limitation is that impact bands used in the present study did not directly map onto those previously developed for use in premenopausal women,[12] in part to facilitate analysis of relationships between Newtest and Actigraph data.

Conclusions

We used a Newtest device to record PA in a population-based study of adolescents. In contrast to conventional approaches, this enables PA to be partitioned according to level of acceleration. We found that high impact activity was relatively rare in adolescents, comprising only 2% of the time spent with light activity. Boys were more active compared with girls, particularly for high impact activity. The extent of PA was inversely related to fat mass and positively related to lean mass. Interestingly, these relationships differed according to impact level, such that high impact activity was related to lean but not fat mass. We conclude that an accelerometer that accurately assesses impact bands may provide additional, more relevant information than conventional accelerometers about the relationship between day-to-day PA and musculoskeletal outcomes.

Funding

UK Medical Research Council (Grant Ref. 74882) and the Wellcome Trust (Grant Ref. 076467) and core support for ALSPAC was provided by the University of Bristol. This specific project was also funded by the Wellcome Trust (Grant Ref. 084632). This article is the work of the authors and J.T. will serve as guarantor for the contents of this article. The references have been checked for accuracy and completeness.

Acknowledgements

We are extremely grateful to all the families who took part in this study, the midwives for their help in recruiting them and the whole ALSPAC team, which includes interviewers, computer and laboratory technicians, clerical workers, research scientists, volunteers, managers, receptionists and nurses.

Conflict of interest: None declared.

KEY MESSAGES

- Using an accelerometer that assesses PA according to the level of impact, we found that exposure to high impact activity was related to lean mass but not to fat mass in adolescents.
- This suggests that the musculoskeletal system preferentially responds to high impact activities.
- Current recommendations to combat obesity by promoting PA by targeting low impact activity like walking are unlikely to affect the musculoskeletal system, unless combined with higher impacts from activities such as jogging, running or jumping.

References

1 Kohl HW, Fulton JE, Casperson C. Assessment of physical activity among children and adolescents: a review and synthesis. *Prev Med* 2000;**31:**S54–76.

2 Mattocks C, Leary S, Ness A *et al*. Intraindividual variation of objectively measured physical activity in children. *Med Sci Sports Exerc* 2007;**39:**622–29.

3 Mattocks C, Leary S, Ness A *et al*. Calibration of an accelerometer during free-living activities in children. *Int J Pediatr Obes* 2007;**2:**218–26.

4 Riddoch CJ, Leary SD, Ness AR *et al*. Prospective associations between objective measures of physical activity and fat mass in 12–14 year old children: the Avon Longitudinal Study of Parents and Children (ALSPAC). *BMJ* 2009;**339:**b4544.

5 Sayers A, Mattocks C, Deere K, Ness A, Riddoch C, Tobias JH. Habitual levels of vigorous, but not moderate or light, physical activity is positively related to cortical bone mass in adolescents. *J Clin Endocrinol Metab* 2011;**96:** E793–802.

6 Goulding A, Taylor RW, Grant AM, Jones S, Taylor BJ, Williams SM. Relationships of appendicular LMI and total body LMI to bone mass and physical activity levels in a birth cohort of New Zealand five-year olds. *Bone* 2009;**45:**455–59.

7 Janz KF, Burns TL, Torner JC *et al*. Physical activity and bone measures in young children: the Iowa bone development study. *Pediatrics* 2001;**107:**1387–93.

8 Harvey NC, Cole ZA, Crozier SR *et al*. Physical activity, calcium intake and childhood bone mineral: a population-based cross-sectional study. *Osteoporos Int* 2011;**23:**121–30.

9 Janz KF, Burns TL, Levy SM *et al*. Everyday activity predicts bone geometry in children: the Iowa bone development study. *Med Sci Sports Exerc* 2004;**36:**1124–31.

10 Janz KF, Gilmore JM, Levy SM, Letuchy EM, Burns TL, Beck TJ. Physical activity and femoral neck bone strength during childhood: the Iowa Bone Development Study. *Bone* 2007;**41:**216–22.

11 Sardinha LB, Baptista F, Ekelund U. Objectively measured physical activity and bone strength in 9-year-old boys and girls. *Pediatrics* 2008;**122:**e728–36.

12 Vainionpaa A, Korpelainen R, Vihriala E, Rinta-Paavola A, Leppaluoto J, Jamsa T. Intensity of exercise is associated with bone density change in premenopausal women. *Osteoporos Int* 2006;**17:**455–63.

13 Goodship AE, Lanyon LE, McFie H. Functional adaptation of bone in increased stress. *J Bone Joint Surg* 1979;**61A:** 539–46.

14 Rubin CT, Lanyon LE. Regulation of bone mass by mechanical strain magnitude. *Calcif Tissue Int* 1985;**37:** 411–17.

15 Martyn-St James M, Carroll S. A meta-analysis of impact exercise on postmenopausal bone loss: the case for mixed loading exercise programmes. *Br J Sports Med* 2009;**43:** 898–908.

16 Golding J, Pembrey M, Jones R. ALSPAC: the Avon Longitudinal Study of Parents and Children. I. Study methodology. *Paediatr Perinat Epidemiol* 2001;**15:** 74–87.

17 Moliner-Urdiales D, Ortega FB, Vicente-Rodriguez G *et al*. Association of physical activity with muscular strength and fat-free mass in adolescents: the HELENA study. *Eur J Appl Physiol* 2010;**109:**1119–27.

18 World Cancer Research Fund. *Food, Nutrition, Physical Activity and the Prevention of Cancer: A Global Perspective*. Washington DC: American Institute for Cancer Research, 2007, pp. 376–377.

19 Cooper C, Westlake S, Harvey N, Javaid K, Dennison E, Hanson M. Review: developmental origins of osteoporotic fracture. *Osteoporos Int* 2006;**17:**337–47.