J Musculoskelet Neuronal Interact 2011; 11(2):196-202

Hylonome

Original Article

Children with low muscle strength are at an increased risk of fracture with exposure to exercise

E.M. Clark[1], J.H. Tobias[1], L. Murray[2], C. Boreham[3]

[1]Academic Rheumatology, Musculoskeletal Research Unit, University of Bristol, Avon Orthopaedic Centre, Southmead Hospital, Bristol. UK BS10 5NB; [2]Centre for Public Health, Institute of Clinical Sciences, Block B, Queens University Belfast, Royal Victoria Hospital, Grosvenor Road, Belfast BT12 6BA; [3]UCD Institute for Sport and Health, University College Dublin, Belfield, Dublin 4

Abstract

Objectives: To use objective measures of physical fitness and muscle function to assess the interplay between exercise, muscle and fractures during childhood. **Methods:** A cross-sectional analysis was performed using The Young Hearts Project, a population-based cohort recruited from Northern Ireland. Grip strength was assessed with a hand-held dynamometer. Aerobic fitness was assessed using the 20-metre endurance shuttle run. The outcome of interest was reported fractures. Data were also collected on other potential confounders. **Results:** There were 787 boys (49.5%) and 803 girls aged 13.9±1.5 years. 414 (26.0%) children reported a fracture at anytime since birth. There was a positive association between higher aerobic fitness and reported fracture (OR 1.23, 95%CI 1.05 to 1.45, P=0.012) greatest in those with lowest grip strength (OR 2.10, 95%CI 1.23 to 3.31, P=0.005). Conversely, in those with highest grip strength, no association was seen between aerobic fitness and reported fractures. **Conclusion:** In children, higher levels of aerobic fitness are associated with an increased risk of fractures, with the greatest risk seen in those with low muscle strength. Our results suggest that there is the potential for exercise protocols that aim to strengthen forearm musculature to reduce upper limb fractures in adolescents.

Keywords: Fracture, Children, Muscle strength, Physical activity

Introduction

Fracture rates during childhood are as high as those in the elderly[1], and the incidence of childhood fractures appears to be increasing for unknown reasons[2]. Physical activity, as assessed by questionnaires, has been shown to be associated with an increased risk of fractures[3,4], and is the strongest predictor of childhood fracture risk found so far[3]. In two large studies, details on habitual physical activity were collected by questionnaires. One study used data on physical activity collected at aged 10 in 2692 children to predict risk of fracture over the following two years[3], whereas the other used sports participation recorded at aged 19 in 7083 young men and found an association with reported fractures from birth up to the point that the activity data were recorded[4]. An explanation for these associations between physical activity and childhood fractures is that reported physical activity is a proxy measure for increased exposure to injury.

As well as being a proxy for exposure to injury, physical activity is likely to directly influence fracture risk by its effects on the musculoskeletal system. It is well-recognised that physical activity is associated with increased bone density and bone size. This has been shown cross-sectionally in large population-based cohorts using objective measures of habitual activity[5], as well as exercise intervention studies[6,7]. The mechanostat theory[8] suggests that mechanical strain is an important determinant of skeletal growth and modelling i.e. bone adapts its strength to the highest peak voluntary load. It has also been shown in large prospective population-based cohorts that increased bone mass is protective for childhood fractures[9].

However, the higher bone mass associated with increased physical activity does not completely compensate for the risk of fracture caused by increased exposure to injuries. This may in part be due to the differing effects of exercise types on muscle mass or strength. Even subtle differences in types of exer-

The authors have no conflict of interest.

Corresponding author: Emma M. Clark, Academic Rheumatology, Musculoskeletal Research Unit, University of Bristol, Avon Orthopaedic Centre, Southmead Hospital, Bristol. UK BS10 5NB
E-mail: emma.clark@bristol.ac.uk

Edited by: F. Rauch
Accepted 20 April 2011

cise can result in measurable differences in specific muscle strength[10]. There is a suggestion that muscle can play a large role in protecting bones from absorbing excess shock, stress or strain[11]. In addition, reduced lower limb lean mass measured by dual energy X-ray absorptiometry (DXA) has been shown to predict lower limb stress fracture over the following 12 months in young adult female athletes[12], and calf-girth is an independent predictor over and above bone density[12]. This suggests that muscle mass may be on the causal pathway from physical activity to fracture, or a modulator of fracture risk.

However, the relationship between physical fitness in broader terms and fracture risk in children is currently unclear. Much work has been done on adults, and particularly military recruits, a group with generally high physical fitness, high levels of physical activity and high exposures to injury. Some of these studies have suggested that lower aerobic fitness compared to peers, assessed by slower timed runs over fixed distances[13,14], is associated with an increased risk of stress fracture, although not all studies agree[15]. In children, the relationship between physical fitness and fracture is likely to be potentially complex: aerobic fitness *per se* could be related to physical activity and therefore be positively related to fracture risk; whereas children with greater muscle strength might be expected to have larger and stronger bones which would be protective. Therefore, in this present investigation we wished to carry out the first population-based study of children assessing the association between objective measures of aerobic fitness, muscle strength and childhood fractures.

Methods

Study design

This study is a cross-sectional analysis using data collected from a population-based cohort recruited from Northern Ireland: The Young Hearts Project.

Study population

The Young Hearts Project was originally set up to examine the prevalence of coronary risk factors in young people aged 12 to 16 years. The sampling procedures employed and the response rates obtained in the initial screening phase are described in detail elsewhere[16], but resulted in a 2% representative sample of Northern Irish schoolchildren. Ethical approval was obtained from the medical research ethics committee of The Queen's University of Belfast, and written consent was obtained from all participating subjects and their parents or guardians.

Main exposure: Objective assessment of muscle function

Isometric grip strength was assessed with a hand-held dynamometer (Takei Scientific Instrument Company Limited, Japan), and measured in kg force: the same measure used in the vast majority of hand grip studies[17]. With subjects standing with their arms held straight by their sides, the dynamometer was gripped as hard as possible for three seconds, without contact with the body and without flexion of the elbow. Two measurements were taken in each arm, with the highest of the measurements recorded and used in the analysis. Maximal vertical jump was measured using a Jump-MD meter (Takei Scientific Instruments Ltd, Japan). Subjects were asked to perform two jumps with their hands on their hips from a standing position. The better of the two attempts (in centimetres) was recorded.

Main outcome: Reported fractures

Information on previous fractures including anatomical location and cause of fracture was collected using a self-report questionnaire completed by each subjects' parent / guardian. For this paper, all reported fractures were used, irrespective of trauma level, as previous work by our group has shown that risk factors such as bone density, for example, predict fractures equally across trauma levels[18].

Secondary exposures: Aerobic fitness and physical activity

Aerobic fitness was assessed using the 20-metre endurance shuttle run (20-MST) previously validated as predictive of maximal aerobic power in the adolescent age group[19], and reported as having a coefficient of variation of 2.2-2.8%[20]. This involves participants repeatedly running back and forth between two sets of markers placed 20 meters apart. Pace is determined by a standardised set of beeps pre-recorded to an initial pace of 8.5 km/hr, and this increases in increments of approximately 0.5 km/hr every minute. Care was taken to ensure correct pacing during the 20-MST by having the investigator run with the subjects throughout each test. Furthermore, a portable heart rate monitor (Polar, Finland) was worn by subjects to ensure that maximum heart rate reached at least 90% of age-related predicted maximum. Participants ran to the point of volitional exhaustion; either they stopped themselves, or were stopped by the test instructor when they failed to complete two consecutive laps in time with the signal.

Questionnaire-based measures of physical activity were used to obtain estimates of habitual activity, and peak strains associated with activity, as reported by many authors[21,22]. Volume of habitual physical activity, encompassing frequency, intensity and duration was estimated using a self-administered seven-day recall questionnaire, the completion of which was supervised by the exercise physiologist. A recall type questionnaire was used in preference to a prospective diary because of the relative ease of administration and completion on the day of testing, and because of the potential of diaries to influence activity patterns during the completion period. In addition, all activities recorded on the questionnaire were assigned an intensity unit based on their rate of energy expenditure expressed as METs (the ratio of the associated metabolic rate for the specific activity divided by the resting metabolic rate). The METS used in this study were a revised version of the Baecke intensity bandings[23].

Other measures

Age and gender were also recorded. Puberty was assessed by a paediatrician who assigned a modified Tanner score (from 1 to 5) to each participant on the basis of non-genital secondary hair growth, vocal timbre, body habitus, and muscular development, and breast development in females[24].

	Participants not reporting a fracture (n=1176) age: 13.8 ± 1.5 years mean (SD)	Participants reporting a fracture (n=414) age: 14.1 ± 1.5 years mean (SD)	P value for difference
Height (cm)	**159.4 (7.9)**	**160.6 (7.9)**	**0.007**
Weight (kg)	52.4 (10.8)	53.6 (10.8)	0.062
Aerobic fitness (laps)	**59.3 (25.6)**	**63.8 (25.6)**	**0.002**
Grip strength (kg)	**23.7 (6.1)**	**24.8 (6.1)**	**0.002**
Vertical jump test (cm)	40.3 (7.6)	41.1 (7.6)	0.063
Habitual activity by Q (max 100)	**24.8 (15.3)**	**26.6 (15.3)**	**0.041**
Forearm BMD (g/cm²)	**0.365 (0.054)**	**0.354 (0.054)**	**0.003**
Pubertal status (Tanner stage)	**1.5 (0.5)**	**1.4 (0.5)**	**0.004**

Table 1. Mean and standard deviation (SD) of anthropometrics, objective and subjective measures of physical activity and forearm BMD for those children with and without reported fractures, adjusted for age. Lines in bold indicate those with a P value <0.05.

Height was measured to the nearest milimeter using a Holtain stadiometer (Holtain Ltd, Crymych, Dyfed). The participant stood erect without shoes, with his/her back to the backboard, heels against the backboard and chin level with the floor. Weight was recorded with the participants wearing light indoor clothing and no shoes, to the nearest 100g, using a Seca 770 electronic weighing scale (Seca Ltd, Hamburg). PIXI (GE Lunar) was used to record bone density at the non-dominant forearm, with the arm positioned according to the manufacturer's instructions so the scan was performed 30 mm from the radius and ulna radiographic junction proximally up the forearm. Socioeconomic status was assessed by self-reported housing tenure, marital status and current employment of the mother.

Statistical analysis

Statistical analyses were carried out by EC using Stata 11.0. Logistic regression was used to calculate odds ratios (ORs) and 95% CIs to describe the associations between variables and the risk of reported fracture. Multivariable regression techniques were used to control for potential confounders such as age, gender or puberty. As our a-priori hypothesis was that muscle function may be on the causal pathway between physical activity and fracture (i.e. an effect modifier), we assessed the association between physical activity and our outcome across tertiles of muscle function. Analysing results separately for gender did not change the point estimates, but reduced the sample size such that confidence intervals crossed zero. In addition, there was no evidence of an interaction (using the Likelihood Ratio Test) between gender and aerobic fitness P=0.922. Results presented are therefore for boys and girls combined apart from where stated. Test for trend P values were calculated by treating the categorical measures as continuous variables in the regression models.

Results

1590 out of 2017 participants (78.8%) had full data for the variables of interest. This study population consisted of 787 boys (49.5%) and 803 girls. Both boys and girls had a mean age of 13.9±1.5 years (the youngest participant was 12.0 years and oldest 16.2 years for both genders). 10.3% of boys were prepubertal compared to 3.0% of girls. 11.5% of girls were postpubertal compared to 3.3% of boys.

In total, 414 (26.0%) children reported a fracture at anytime since birth, but more boys fractured than girls (29.2% vs 22.9%, P=0.004). 74.4% of fractures were of the upper limb and 19.9% of the lower limb. The children with reported fractures were slightly older than the children with no fractures (14.1±1.5 years vs 13.8±1.5, P=0.011), so all further analyses are adjusted for age. The most common sports played for a school team were soccer (40.3% of boys and 9.9% of girls), hockey (3.2% of boys and 32.3% of girls), netball (24.8% of girls), rugby (17.6% of boys) and gaelic sports (11.7% of boys). No one sport type was associated with a higher risk of reported fracture (P=0.321).

Children with fractures were taller, did more habitual physical activity as assessed by questionnaire and had greater aerobic fitness and grip strength than children without reported fractures (Table 1), and had lower forearm BMD. There was a trend with the vertical jump test to be positively associated with reported fractures, but this did not reach statistical significance. No association was seen between puberty, ethnicity, socioeconomic status (results not shown) or weight and reported fractures. There was a positive association between tertiles of aerobic fitness and fracture risk (Table 2) that was independent of height, weight and grip strength (OR Test for Trend 1.23, 95%CI 1.05 to 1.45, P=0.012). This positive association was also seen in boys (OR 1.17, 95%CI 0.90 to 1.51) and girls (OR 1.17, 95%CI 0.91 to 1.51) with minimal change in the point estimate, but confidence intervals crossing zero because of reduced sample size. Analyses were repeated, first limiting reported fractures to those of the upper limb (OR Test for Trend 1.21, 95%CI 1.01 to 1.46, P=0.039), and then limiting to reported fractures of the lower limb (OR Test for Trend 1.29, 95%CI 0.89 to 1.86, P=0.181), and results were similar. No association was seen between grip strength and fractures after adjusting for aerobic fitness (Table 2). Interestingly, an association

	OR for fracture risk adjusted for age OR (95%CI)	OR for fracture risk adjusted for all other variables in table and age OR (95%CI)
Aerobic fitness (tertiles)		
low	**1.0**	**1.0**
medium	**1.17 (0.88, 1.56)**	**1.19 (0.89, 1.60)**
high	**1.52 (1.15, 2.01)**	**1.50 (1.08, 1.60)**
	OR Test for Trend	***OR Test for Trend***
	1.23 (1.07, 1.42), P=0.004	**1.23 (1.05, 1.45), P=0.012**
Grip strength (tertiles)		
low	**1.0**	1.0
medium	**1.05 (0.78, 1.41)**	0.93 (0.68, 1.28)
high	**1.50 (1.06, 2.12)**	1.06 (0.69, 1.64)
	OR Test for Trend	***OR Test for Trend***
	1.23 (1.03, 1.46), P=0.022	1.02 (0.82, 1.27), P=0.832
Height (per 5 cm increase)	**1.10 (1.03, 1.18), P=0.007**	1.03 (0.94, 1.14) P=0.500
Weight (per kg increase)	**1.05 (0.99, 1.03), P=0.063**	1.04 (0.97, 1.12) P=0.232

Table 2. Odds ratios (ORs) for fracture risk according to aerobic fitness, grip strength and height or weight. Results are shown adjusted for age, and adjusted for age and all other variables in the table. Lines in bold indicate those with a P value <0.05.

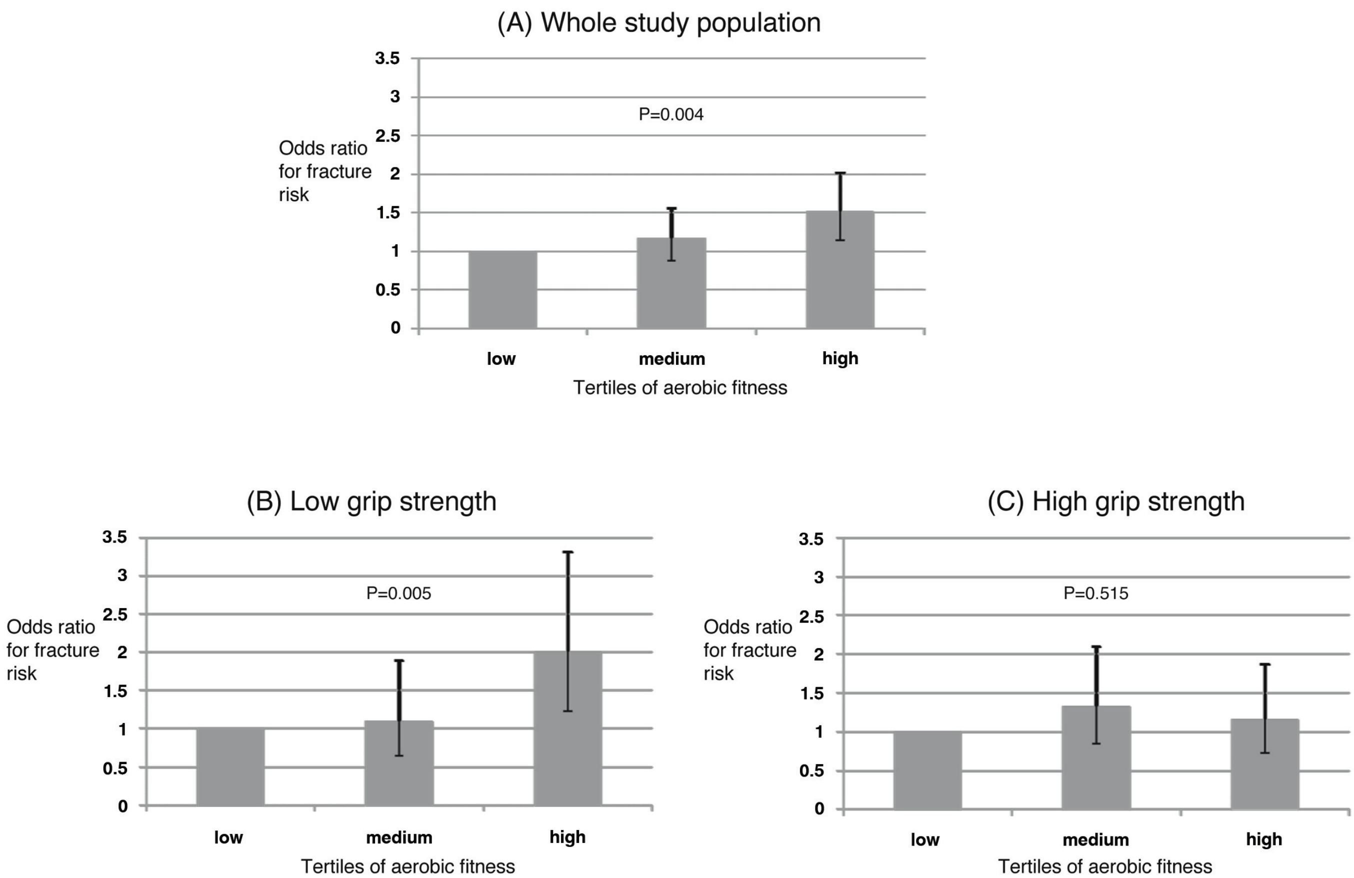

Figure 1. Graphs showing odds ratios and 95% confidence intervals (error bars) for risk of reported fractures according to tertiles of aerobic fitness in (A) the entire study population (n=1590), (B) those with grip strength in the lowest tertile (n=531) and (C) those with grip strength in the highest tertile (n=527). P values are Test for Trend, and results are adjusted for age.

was still seen between aerobic fitness and all reported fractures after adjusting for habitual activity in addition to adjustment for age, height, weight and grip strength (OR Test for Trend 1.21, 95%CI 1.02 to 1.44, P=0.033). As expected, there was a strong positive association between grip strength and all our bone mass measures: BMD, BMC or area (P<0.001).

To further analyse potential modifying effects of muscle function on the association between aerobic fitness and reported fractures (Graph A, Figure 1) we analysed across tertiles of muscle function, and showed that in those with grip strength in the lowest tertile, the positive association between fitness and fractures still held (Graph B, Figure 1). Those with highest aerobic fitness but lowest grip strength had an elevated risk of reported fracture (OR 2.10, 95%CI 1.23 to 3.31, P=0.005). Conversely, in those with grip strength in the highest tertile, no association was seen between aerobic fitness and reported fractures (Graph C, Figure 1). Adjustment for gender, height, habitual activity assessed by questionnaire, and forearm BMD did not alter these associations (results not shown). Similarly, those with the highest aerobic fitness but lowest vertical jump test results had an elevated risk of reported fracture (OR 1.71, 95%CI 1.03 to 2.84, P=0.037), whereas no association was seen between aerobic fitness and fracture in those with the highest vertical jump test results. Fourty-eight % of children in the low grip strength group had low levels of aerobic fitness, and 18.8% had high levels. In the high grip strength group 15.4% had low levels and 56.0% had high levels of fitness.

Discussion

Our results show that higher levels of aerobic fitness in children are associated with a higher risk of fractures. Furthermore we have shown that muscle strength is an effect modifier for this association, and the greatest risk of fracture with higher aerobic fitness is seen in those with low muscle strength. To our knowledge this is the first time this interplay between aerobic fitness, muscle strength and fractures has been addressed in children.

Our previous work on a population-based cohort of 2692 children used a questionnaire-based measure of physical activity collected when the children were aged 9 and showed that high levels of vigorous physical activity per week predicted fractures over the following two years[3]. Similarly, our current study using objective data from the Young Hearts project supports the hypothesis that aerobic fitness may serve as a proxy for exposure to injuries via physical activity. Alternatively, it is possible that increased aerobic fitness is associated with fractures for other reasons. Persistence of the association between aerobic fitness and reported fractures was not altered by adjustment for habitual activity, suggesting that aerobic fitness may not be simply a proxy for injury. An alternative explanation could be that increasing aerobic fitness is associated with 'excessive' training which may adversely affect general skeletal health as seen in female athlete triad, long distance runners[25] and competitive cyclists[26].

Previous studies have shown that children[27] and young adults[28,29] with a history of fractures have reduced muscle cross-sectional area: our study extends these observations and shows that muscle *function* i.e. strength, modifies the association between higher aerobic fitness and increased fracture risk. Muscle function measured by grip strength is likely to be related to muscle mass, which is in turn a strong determinant of bone size[30], bone volumetric density[31] and associated bone strength. Large prospective studies have shown that, per standard deviation decrease in bone mass, fracture risk in children approximately doubles[9], and so it is likely our measure of low grip strength is influencing the causal pathway between physical activity and fractures by this mechanism.

Furthermore, it is thought that muscle function may play both a causative and a protective role in the occurrence of fractures[32]. For example, occasionally the damaging role is seen in rowers who may develop stress fractures of the ribs due to excess muscle torque rather than external reaction forces[33]. Conversely, muscles can protect bones by absorbing excessive shock, stress or strain[28]. So despite the fact that they may exert more torque, larger muscles will also have the ability to directly absorb shock and also reduce shear (seen at the tibia for example during running[34]), thereby reducing stress to the bone and reducing the risk of fractures. Our children with lower grip strength may be at increased risk of fractures with greater physical activity because of the reduced ability of their muscles to absorb shock and protect bones.

Furthermore, our results suggest that interventions to improve muscle size and function may reduce fracture risk, corroborating the conclusions of a recent study on military recruits[28]. However, prospective research is necessary to determine whether childhood fracture incidence may be reduced through interventions to improve muscle function.

There are limitations to our study, particularly the fact that it is cross-sectional in nature. In addition, it is unknown if low observed grip strength is a direct effect of a recent fracture causing immobility of the dominant arm, or whether it was present prior to fracture. We aimed to mitigate this by using the greatest observed grip strength after testing both arms. Furthermore, some studies show no lasting effect of previous childhood fractures on muscle strength. For example, in a case-control study of 31 children with previous fractures and a group of matched controls no difference was seen in muscle strength 1.5 to 5 years after the original fracture[35]. We also used reported fractures as an outcome, not verified fractures, and it is inevitable that some children will have been incorrectly classified as fractured or not. However, rather than produce spurious results this is likely to reduce the strength of any association seen towards the null. In addition, the reported fractures will have occurred after varying levels of trauma and in various bones including skull, that may be unrelated to muscle parameters. Again this will simply reduce the strength of any association seen. Further limitations in our study, in common with all observational studies, include unmeasured confounding and chance. One such unmeasured confounder may be behavioural characteristics such as competitiveness or risk-taking which could be associated with both performance during our aerobic fitness test and fracture risk. Finally, the use of a seven-day recall questionnaire may not adequately address lifetime or habitual activity exposure.

Although upper extremity muscle function appeared to moderate fracture risk associated with high physical fitness, no such association was demonstrated for lower extremity muscle function (jump height). This is likely to be because the majority of childhood fractures affect the upper limb[3], and therefore we were actually identifying an association between reduced upper limb muscle function and upper limb fractures. This agrees with studies which report that local muscle size influences local bone mass[30] and confirmed by our results. Due to the relatively low number of lower extremity fractures represented we did not have the power to find an association between reduced muscle function of the lower limb and lower limb fractures. Furthermore, in this analysis we did not separate out the specific types of physical activity or sports participation, and therefore were unable to identify those activities that are associated with high aerobic fitness and high muscle function, which should be promoted as sports which will increase aerobic fitness without increasing fracture risk.

So, in conclusion, we have shown that in children, higher levels of aerobic fitness are associated with an elevated risk of fractures. However, this phenomenon appears to be predominantly associated with individuals of high fitness but low local muscular strength, as fit subjects with high grip strength did not exhibit elevated risk. Our results suggest that there is the potential to reduce the burden of upper limb fractures in adolescents by exercise protocols that aim to strengthen forearm musculature and improve bone strength.

Acknowledgements

The YH2000 project was funded by a grant from the Department of Health and Social Services in Northern Ireland

References

1. Alffram PA, Bauer GCH. Epidemiology of fractures of the forearm. J Bone Joint Surg Am 1962;44:105-114.
2. Khosla S, Melton LJ, Dekutoski MB, Achenbach SJ, Oberg AL, Riggs BL. Incidence of childhood distal forearm fractures over 30 years: A population-based study, JAMA 2003;290:1479-1485.
3. Clark EM, Ness AR, Tobias JH. Vigorous physical activity increases fracture risk in children irrespective of bone mass: A prospective study of the independent risk factors for fractures in healthy children. J Bone Miner Res 2008;3:1012-1022.
4. Matilla WM, Jormanainen V, Sahi T, Pihlajamak H. An association between socioeconomic, health and health behavioural indicators and fractures in young adult males. Osteop Int 2007;8:1609-1615.
5. Tobias JH, Steer CD, Mattocks CG, Riddoch C, Ness AR. Habitual levels of physical activity influence bone mass in 11-year-old children from the UK: Findings from a large population-based cohort. J Bone Miner Res 2007;2:101-109.
6. MacKelvie KJ, Khan KM, Petit MA, Janssen PA, McKay HA. A school-based exercise intervention elicits substantial bone health benefits: A 2-year randomized controlled trial in girls. Pediatrics 2003;112:447-452.
7. Bradney M, Pearce G, Naughton G, Sullivan C, Bass S, Beck TJ, Carlson J, Seeman E. Moderate exercise during growth in prepubertal boys: Change in bone mass, size, volumetric density, and bone strength: A controlled prospective study. J Bone Miner Res 1998;13:1814-1821.
8. Frost HM. Bone's mechanostat: a 2003 update. Anat Rec A Discov Mol Cell Evol Biol 2003;275:1081-1101.
9. Clark EM, Ness AR, Bishop NJ, Tobias JH. Association between bone mass and fractures in children: A prospective cohort study. J Bone Miner Res 2006;21:1489-1495.
10. Bojsen-Moller J, Larsson B, Magnussun SP, Aagaard P. Yacht type and crew-specific differences in anthropometric, aerobic capacity, and muscle strength parameters among international Olympic class sailors. J Sports Sci 2007;25:1117-1128.
11. Giladi M, Milgrom C, Simkin A, Danon Y. Stress fractures: identifiable risk factors. Am J Sports Med 1991;19:647-652.
12. Bennell KK, Malcolm SA, Thomas SA, Reid SJ, Brukner PD, Ebeling PR, Wark JD. Risk factors for stress fractures in track and field athletes: A twelve-month prospective study. Am J Sports Med 1996;24:810-818.
13. Rauh MJ, Macera CA, Trone DW, Shaffer RA, Brodine SK. Epidemiology of stress fracture and lower-extremity overuse injury in female recruits. Med Sci Sports Exer 2006;38:1571-1577.
14. Shaffer RA, Brodine SK, Almeida SA, Williams KM, Ronaghy SW. Use of simple measures of physical activity to predict stress fractures in young men undergoing a rigorous physical training program. Am J Epi 1999;149:236-242.
15. Swissa A, Milgrom C, Giladi M, Kashtan H, Stein M, Margulies J, Chisin R, Aharonson Z. The effect of pretraining sports activity on the incidence of stress fractures among military recruits: A prospective study. Clin Orthop and Rel Res 1989;245:256-260.
16. Boreham C, Savage JM, Primrose D, Cran G. J Strain, Coronary risk factors in school children. Arch Dis Child 1993;68:182-186.
17. Gale CR, Martyn CN, Cooper C, Sayer AA. Grip strength, body composition and mortality. Int J Epi 2007;36:228-235.
18. Clark EM, Ness AR, Tobias JH. Bone fragility contributes to the risk of fracture in children, even after moderate and severe trauma. J Bone Miner Res 2008;23:173-179.
19. Boreham CA, Palikzka VJ, Nichols AK. A comparison between the PWC170 and 20-MST tests of aerobic fitness in adolescent school children. J Sports Med Phys Fitness 1990;30:19–23.
20. Nassis GP, Geladas ND, Soldatos Y, Sotiropoulos A, Bekris V, Souglis A. Relationship between the 20-m multistage

shuttle run test and 2 soccer-specific field tests for the assessment of aerobic fitness in adult semi-professional soccer players. J Strength Cond Res 2010;24:2693-2697.
21. Kemper HCG, Bakker I, Twisk JWR, van Mechelen W. Validation of a physical activity questionnaire to measure the effect of mechanical strain on bone mass. Bone 2002;30:799-804.
22. Stager MJ, Harvey R, Secic M, Camlin-Shingler K, Cromer B. Self-reported physical activity and BMD in urban adolescent girls. J Ped Adoles Gyne 2006;19:17-22.
23. Baecke JAH, Burema J, Frijters JER. A short questionnaire for the measurement of habitual physical activity in epidemiological studies. Am J Clinl Nutr 1982;36:936-942.
24. Tanner JM, Growth At Adolescence. 2nd Edition, Oxford: Blackwell Scientific Publications, 1962.
25. Pollock N, Grogan C, Perry M, Pedlar C, Cooke K, Morrissey D, Dimitriou L. BMD and other features of the female athlete triad in elite endurance runners: a longitudinal and cross-sectional observation study. Int J Sport Nutr Exerc Metab 2010;20(5):418-426.
26. Beshgetoor D, Nichols JF, Rego I. Effect of training mode and calcium intake on BMD in female master syslist, runners and non-athletes. Int J Sport Nutr Exerc Metab 2000;10(3):290-301.
27. Schoenau E, Neu CM, Beck B, Manz F, Rauch F. BMC per muscle cross-sectional area as an index of the functional muscle-bone unit. J Bone Miner Res 2002;17:1095-1101.
28. Popp KL, Hughes JM, Smock AJ, Novotny SA, Stovitz SD, Koehler SM, Petit MA. Bone geometry, strength, and muscle size in runners with a history of stress fracture. Med Sci Sports Exer 2009;41:2145-2150.
29. Beck TJ, Ruff CB, Shaffer RA, Betsinger K, Trone DW, Brodine SK. Stress fracture in military recruits: gender differences in muscle and bone susceptibility factors. Bone 2000;27:437-444.
30. Heinonen A, McKay HA, Whittall KP, Forster BB, Khan KM. Muscle cross-sectional area is associated with specific site of bone in prepubertal girls: A quantitative MRI study. Bone 2001;29:388-392.
31. van Langendonck L , Claessens AL, Lysens R, Koninckx PR, Beunen G. Association between bone, body composition and strength in premenarchal girls and postmenopausal women. Ann Human Biol 2004;31:228-244.
32. Donahue S. The role of muscular force and fatigue in stress fractures. In: Burr DB, Migrom C, editors. Musculoskeletal Fatigue And Stress Fractures. CRC Press; 2001. p. 131-150.
33. Karlson KA. Rib stress fractures in elite rowers: a case series and proposed mechanism. Am J Sports Med 1998;26:516-519.
34. Sasimontonkul S, Bay B, Pavol M. Bone contact forces on the distal tibia during the stance phase of running. J Biomech 2007;40:3503-3509.
35. Hedin H, S Larsson S. Muscle strength in children treated for displaced femoral fractures by external fixation: 31 patients compared with 31 matched controls. Acta Orthop Scand 2003;74:305-311.