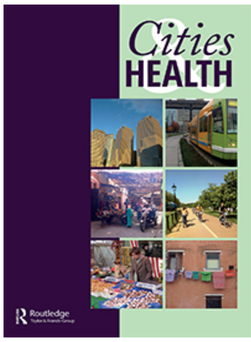

Cities & Health

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/rcah20

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To cite this article: Anna Boldina, Beatriz Gomes & Koen Steemers (2021): Active urbanism: The potential effect of urban design on bone health, Cities & Health, DOI: 10.1080/23748834.2021.1921512

To link to this article: https://doi.org/10.1080/23748834.2021.1921512

CITIES & HEALTH
https://doi.org/10.1080/23748834.2021.1921512

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Active urbanism: The potential effect of urban design on bone health

Anna Boldina [a], Beatriz Gomes [b] and Koen Steemers [a]

[a]The Martin Center of Architectural and Urban Studies, Department of Architecture, University of Cambridge, Cambridge, UK; [b]Research Unit for Sport and Physical Activity (CIDAF), Faculty of Sport Sciences and Physical Education, University of Coimbra, Coimbra, Portugal

ABSTRACT
Health is becoming an increasingly important aspect of built environment design. We aim to bridge the gap between existing knowledge in medicine and its potential applications. This paper tests the extent to which Active Urbanism can facilitate gaining and maintaining bone mass widely across the population through encouraging serendipitous high impact exercise. Based on a review of successful high impact exercise programs, we run a biokinetics experiment in a laboratory measuring ground reaction forces to match field sociological studies in the urban environment. Considering data collected, Active Urbanism can increase the average bone density of an average child not previously involved in sport by 12% in 10 years, and that of an average adult by 2.8% in 10 years. Such a modest increase in bone mass density, if sustained over a lifetime, has the potential to delay the risk of fracture and of osteoporosis by 10 years or more. This new parameter has the potential to support infrastructure and landscape designers to optimize their plans and will need further examination by communities of these practices.

ARTICLE HISTORY
Received 31 October 2020
Accepted 20 April 2021

KEYWORDS
Health; active urbanism; osteoporosis; playful environment; hight impact exercise

Introduction

Health is the key component of a long life, and a healthy body widens an individual's opportunities to make every day more enjoyable. While to some extent health is determined by genetics, it is also largely influenced by lifestyle and the environment, and hence can be improved (Foster *et al.* 1995, Guthold *et al.* 2018). Epidemiologist Geoffrey Rose suggested that a state's effort to reduce the number of sick people would be more effective if diverted towards shifting an entire population's health distribution rather than concentrating only on the high-risk unhealthy minority (Rose 1993) (Figure 1).

Physical activity is one of the known ingredients of a healthy lifestyle; however, high levels of inactivity are still present throughout the world's population. There are multiple vectors that might push a person towards exercising or repulse them from it, and the nature of the urban environment has proven to make a significant difference. Recent studies have shown that many lifestyle decisions are made based on impulses, 'thinking fast', rather than logic and aiming for remote goals by 'thinking slow' (Ekkekakis 2003, Kahneman 2018). The design of the built environment can offer immediate exercise opportunities avoiding the logistics of travel, booking, arranging to meet with others and planning the day in advance.

Local governments are starting to adopt more structural interventions to nudge the population into physical activity, for example, by designing walkable enjoyable routes, cycling paths, parkour and skating sites and outdoor gyms (Thaler and Sunstein 2009, Gilchrist and Wheaton 2011, Ameel and Tani 2012, Wood *et al.* 2014, Rutter *et al.* 2017, Sennett and Sendra 2020), but it is possible to do more, particularly to encourage unconscious, unplanned or serendipitous everyday physical activity.

The connection between the built environment and health and wellbeing has received increased scientific and urban planning practice-based attention in recent decades (Baker *et al.* 1993, Barton and Tsourou 2000, Grant 2015, Steemers 2015, Healthy Streets for London 2017, Fudge *et al.* 2020). The Mayor of London adopted a set of principles to make the capital healthier, including resting places allowing older people to walk and stay active, noise reduction and others (Healthy Streets for London 2017, Plowden 2020). There is an unexplored potential of the built environment effect through types of encouraged locomotion: improving proprioception with stepping stones and balancing curbs, cardiovascular improvements by walking up slopes and helping mental health through design that enhances mindfulness. While unknown in architecture, special landscape strategies are already used in health management to slow the aging process (Lappset senior playgrounds) and correct various disorders, such as genetic orthopedic deformities in children (CCBRT

CONTACT Anna Boldina ab2509@cam.ac.uk Christ's College, University of Cambridge, Cambridge, UK

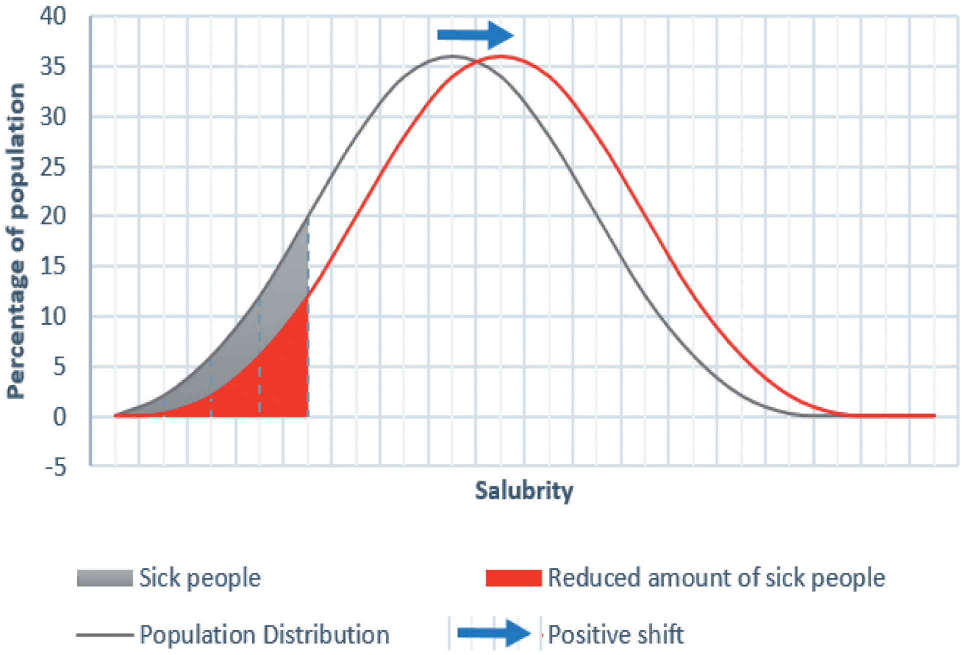


Figure 1. The population strategy of health. (Combined data used from Rose 1993, Cooper and Melton 1992).

hospital in Dar Es Salaam, Tanzania). Reflexology routes with cobblestones are popular in Asia and studies show they can be effective in lowering high blood pressure (Li *et al.* 2005). Urban Gym takes groups from offices out for circuit training in the urban environment using steps, balustrades, benches and walls (Allison 2020).

This paper explores the opportunities that the urban environment can provide to maintain and develop bone mass, which is key for preventing osteoporosis and fractures, especially stress fractures. The other benefits of serendipitous exercises for physical and mental health will be reported in subsequent research.

Biophysics theory

Bone mineral density normally increases from the beginning of life until the age of 18–30 years, depending on body part and individual characteristics, and slowly decreases after that (Cooper and Melton 1992, Kröger *et al.* 1993). For example, in the femoral neck the peak occurs at age 16 to 19 years in women (0.981 g/cm^2) and 19 to 21 years in men (1.093 g/cm^2) (Berger *et al.* 2010) (Figure 2). Peak Bone Mass is an important determinant for the risk of osteoporosis in later life (Riggs and Merton 1992, Henry *et al.* 2004, Gallo *et al.* 2012). An increase of Peak Bone Mass

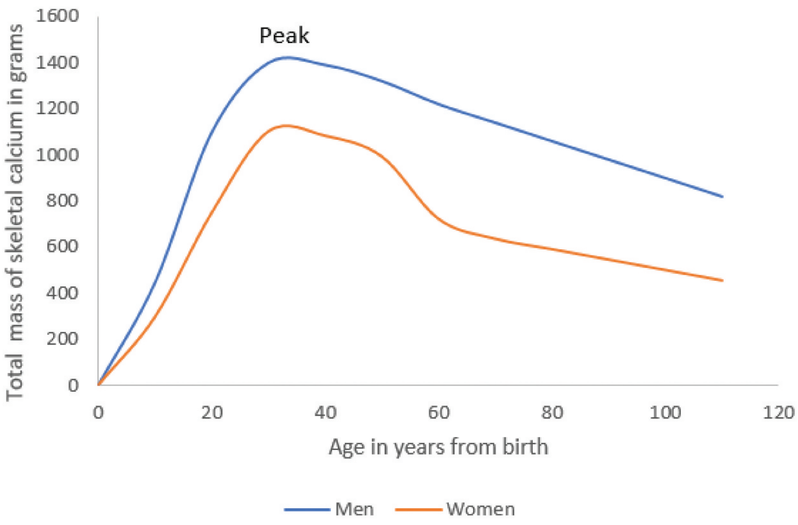


Figure 2. Age changes in skeletal calcium mass (Data from Riggs and Merton 1992, Henry *et al.* 2004).

by 10% could delay osteoporosis by 13 years and decrease the risk of fragility fracture by 50% (Ott 1990, Daly *et al*. 1999, Hernandez *et al*. 2003, Rizzoli *et al*. 2010, Anliker *et al*. 2012) (Figure 3).

After the age of approximately 40 years, bone mineral mass decreases by 3% every decade in both sexes, but in women additional loss occurs after the menopause, bringing their total rate of decrease to 9% per decade between 45 and 75 years. Thus, most adults are, to some degree, in the process of developing osteopenia and are likely to have osteoporosis eventually if they live sufficiently long (Hernandez *et al.* 2003).

Bone density is usually measured using dual energy x-ray absorptiometry (DEXA) and stated in terms of Standard Deviations in comparison to the bone density of a young healthy adult (T-score). Osteopenia is identified between 1.0 and 2.5 Standard Deviations below this point, and osteoporosis beyond 2.5.

Maintaining a body fit for purpose requires the bone mass and architecture of the skeleton to continuously adjust to the physical forces exerted on it: compressive, tensile, bending, and torsional. These adjustments ensure that the skeleton maintains the ability to withstand static and dynamic functional loads without fractures. Like building structures, resistance to compression and torsion of a bone is proportional to the amount and distribution of bone material (Lanyon 1992). According to the mechanostat theory of Harold Frost based on Julius Wolff's law, intrinsic muscle force leads to bone deformation creating bone strain (Turner 1998). When these bone strains exceed a threshold (~2000 µStrain), the bone adapts its bone mass and geometry (Ott 1990, Anliker *et al*. 2012). The effect can be illustrated by the difference in the arms of tennis players: the bones of the arm used to hold the racquet are wider and have up to 26% more mineral content than those of the opposite arm (Kannus *et al.* 1995). Bones that experience no strain lose mineral density, for example in people unable to move or in astronauts in space missions (Shackelford *et al*. 2004). The other determinants of bone architecture are genetics and diet. Obesity is correlated with the increased bone mass.(Zhao *et al*. 2007)

A number of papers explore the effect of various types of exercises on bone mass. Research has shown that smooth-motion exercise, such as cycling or swimming, though it has multiple positive effects on health, has little or no effect on bone structure (Guadalupe-Grau *et al*. 2009). The most effective exercises for gaining and maintaining bone mass are load-bearing or high impact exercises with dynamic forces delivered to the skeleton, such as running, jumping, tennis, squash, gymnastics, ice hockey, volleyball, and soccer. The crucial factor in the stimulation of the bone response seems to be load magnitude rather than the number of repetitions (Kemper *et al*. 2000). Short bouts with periods of rest in between appear to be most effective for the osteogenic response to loading (Lanyon 1992, Heinonen *et al.* 1996, Rector *et al.* 2008, Guadalupe-Grau *et al.* 2009; Karl Karlsson and Erik Rosengren 2012).

Some older people avoid jumping due to perceived danger for the joints and the possibility of developing osteoarthritis, but studies show that while excessive stresses in professional athletes might cause osteoarthritis, leisure-time physical

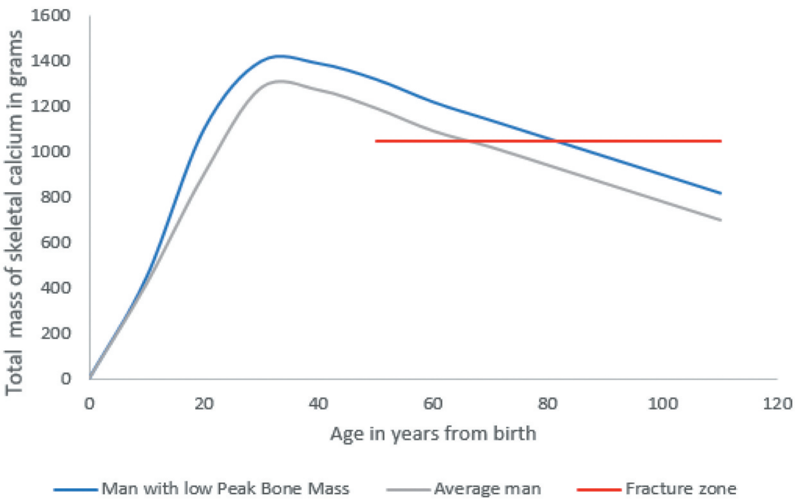


Figure 3. Schematic representation of the changes of bone mass with age. The grey line shows the theoretical consequence of a reduction in peak bone mass.(Data from (Ott 1990, Daly *et al*. 1999, Hernandez *et al*. 2003, Rizzoli *et al*. 2010, Anliker *et al*. 2012).

activity reduces the risk of developing it (Rogers *et al.* 2002).

People who are over 50 years old now and make up the bulk of osteoporosis case statistics gained their bone mass before 1980. A drop in children's street activity in the UK from 75% in 1973 to 15% in 2008 (Brockman *et al.* 2011) means that people who are in their 20s now were 5 times less involved in street activity as children (Figure 4). The perception of acceptable risk is changing: climbing is now often limited to dedicated playgrounds in parks, but even those areas are often seen as unsafe by parents (ARUP 2020). If today's growing children are developing a skeleton with a lower peak bone mass than 50 years ago, then fracture numbers might increase, although no long-term studies are available to support this assumption (Karlsson *et al.* 2008).

The process of elimination of opportunities for pedestrians of all ages to challenge themselves that is underway in the UK now was meant to help avoid falls and improve population health, but might lead to unexpected negative long-term effects.

Review of gym experiments methodology and results

To estimate the potential effect of the urban environment on bone strength we reviewed the methodology and results of four experiments in Table 1. The loads were measured by Kistler Z4852/c, Kistler 9286AA and Kistler 9281B force platforms.

Figure 4. Child playing, Moorgate, London, 1946.

Table 1. Forces in 3 dimensions from stepping down and jumping down 385 mm - experimental data for 17 subjects.

Location, reference	Subjects	Test group	Load (times body weight	Experiment length	Result Test group	Control group	N of jumps
Melbourne (Daly *et al.* 1999)	Pre- and peripubertal male subjects (~10 years old)	Various high-impact gymnastic exercises loading bones with rapidly rising forces	Arms 1.5 to 3.6; legs 3.7 to 10.4	18 months	12.8% increase in broadband ultrasonic attenuation (reflecting bone density) at the heel bone	7.2%	
Oregon (Fuchs *et al.* 2001)	Children 5–10 years old, both genders	100 jumps each session at their own time with both feet off 61 cm boxes (3 times per week)	7.9 to 9.7	7 months	Femoral neck increased by 3.6%,	2.4%	7300
Nottingham (Bassey *et al.* 1998)	Pre- and postmenopausal women	Performed 50 jumps with an average jump height of 8 cm	3.0 in the younger and 4.0 in the older women.	5 months	Pre-menopausal women: increase of 2.8% in femoral bone mineral density	Insignificant effect on post-menopausal women	6300
Leicester (Allison *et al.* 2013)	Men aged 65–80 years	5 sets of 10 multidirectional hops on one randomly allocated exercise leg between 2 and 3 min in total, 7 days a week	2.7 to 3.0	12 months	Lower neck bone mineral density increased in exercise leg by 1.4%	Decreased in the control leg by 0.8%	18,250

Short bouts of dynamic load with a few hours of rest in between are likely to give a stronger osteogenic response than continuous physical activity once or twice a week (Hernandez *et al.* 2003, Ivy and Knight 2006, Karl Karlsson and Erik Rosengren 2012). Studies on animals showed that increasing the rest periods between bouts of loading did not mitigate the osteoblastic response (Srinivasan *et al.* 2015) and that 5 jumps a day produced a noticeable effect on bone architecture, while increasing the amount of jumps to 10, 50 and 100 enhanced this effect only slightly (Umemura *et al.* 1997, Srinivasan *et al.* 2015). Reactions to loads in bones are slower than in other parts of the body – one remodeling cycle of bone resorption, formation, and mineralization takes 3 to 4 months to complete (Goolsby and Boniquit 2017). The above suggests that receiving regular skeleton loadings over a given period of time would be no less and probably more efficient than concentrating the same number of loadings over a short period of time and then not exercising for the rest of that period.

The effect remains for years after practicing gymnastics: 22–30 years old female subjects retired from gymnastics 10 years before the measurement showed 14% higher Bone Mineral Density than the control group of the same age who never did gymnastics (Erlandson *et al.* 2012). Men who did weightlifting in their youth maintained higher bone mineral density even 30 years later than controls of the same age group (Karlsson *et al.* 1995). Another cross-sectional study showed that women who jog at least once a week had 1.4% greater bone mineral content at 38–49 years and by 12% at 50–59 years (Jónsson *et al.* 1992).

Ironically, people who feel fragile reduce their level of activity hoping to reduce the risk of bone damage, but as a result bone loss increases and hence the risk of fractures (Reventlow 2007).

Significance of the study

Worldwide, 1 in 3 women and 1 in 5 men are likely to experience osteoporotic fractures in their lifetime. Approximately a third of hip fracture patients require nursing home care and suffer from social isolation and decreased mobility, quality of life and self-esteem (Hart *et al.* 2017). For those over 50 years old, mortality in the first year after sustaining a hip fracture is over 30% (Sözen *et al.* 2017). Each year 500,000 patients are treated in hospitals with fractures caused by osteoporosis, costing the NHS an estimated £4.4 billion a year (NICE 2018). As life expectancy is increasing, osteoporosis prevalence and fractures might increase with it (Hernandez *et al.* 2003). Hence if accounting for bone health in Urban Design could have an effect, it would improve the lives of a significant portion of the population.

The cross-sectional and longitudinal studies above showed that exercise programs can be highly successful in both gaining bone mass at young age and maintaining it in later life. If an average person was enrolled into those programs from childhood until older age, their bone mass could be 12–18% greater (Erlandson *et al.* 2012). Taking into account that gaining 10% of bone mass decreases the risk of osteoporosis by 50% (Hernandez *et al.* 2003) the number of people affected by osteoporosis in the UK could speculatively fall from the current figure of over 3 million ('NHS' 2018) to under 1.5 million.

However, the downside of exercise programs is the necessity for strong dedication and control. Even in the course of the tests above, despite knowing the scientific importance of research and benefiting from the support of physiologists, many of the subjects dropped out during programs lasting several months (Bassey *et al.* 1998).

How could we involve the whole population in a lifelong exercise program by means of city design?

Methodology

We decided to find out if dynamic loads similar to the experiments above can be delivered to the skeleton through urban interventions, allowing people to trigger an osteogenic response by everyday walking through the urban environment instead of dedicated exercise in a gym.

With a series of pilot studies in city environments in Portugal and London (Figure 5) we identified stepping

Figure 5. Observations of stepping down.

down 300–450 mm as mildly challenging so most people are not afraid or uncomfortable to do it as part of normal walking. This is 2–3 times higher than a standard 150 mm step. We test if sufficient strains on the body can be achieved by stepping down from this height.

Shortcut in Hackney, North-Central London

After crossing Packington Bridge over Regent's canal, there are two ways to turn left and down to the Canal Walk: 47 meters around down a slope, which takes on average 36 sec (Route A), or 7 meters across the planter and stepping 470 mm down, which takes 7 sec (Route B), so picking the second route saves 29 sec (Figure 6). 65% of pedestrians chose Route B.

Biokinetic experiment

Method

A Kistler Piezoelectric 3D Force Plate 9260AA6, the same brand as was used in the gym experiments above, was used to identify vertical and horizontal forces. When a subject applies force to the ground (platform) there is an equal and opposite reaction from the ground (Figure 7).

The plate was connected to a laptop, and data were recorded using the manufacturer's BioWare Version 5.3.2.9 software. The platform is 50 mm thick. The experiment equipment had to be connected to a power supply, so we re-created the shapes from the urban environment in the Integrated Laboratory of the Faculty of Sport Sciences and Physical Education of Coimbra University, Portugal.

Subjects were recruited from the Sport Sciences and Physical Education Faculty: 9 male, 8 female, 18–40 years old, 172 ± 19 cm tall with BMI 22 ± 6. Subjects with a history of significant cardiovascular, pulmonary, metabolic, and musculoskeletal diseases were excluded.

An experiment conducted at ETH Zurich with various age groups showed that walking on a flat surface as well as walking up any stairs and down flat stairs created ground reaction forces just above body weight, and walking down steep stairs with 200 mm treads created forces close to 150% of body weight (Stacoff *et al.* 2005), fare below the 300% reached in the exercise programs above (Figure 8).

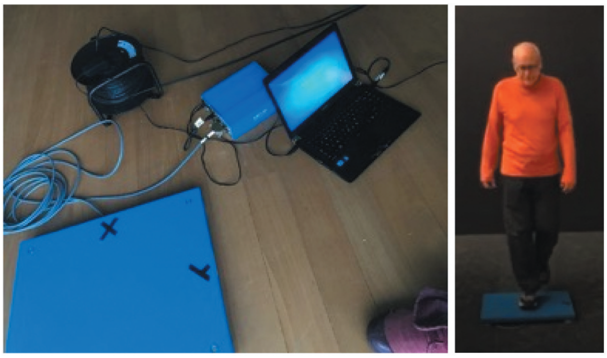


Figure 7. Kistler Force Plate 9260AA6 used in the experiment.

To identify the direction of research we ran a pilot study on 3 subjects: female, 37 (F37, with and without boots), female 40 years old (F40) and male 67 years old (M67) using a Kistler force plate. Subjects were required to step up 305 mm (back leg force measured) and 405 mm (front leg force measured), step down 305 mm (front leg force measured), and walk on an even surface. The results were as follows:

Step up 305 mm, back leg force measured: 173% of body mass (Figure 9).

Step up 405 mm, front leg force measured: 107.5% of body mass (Figure 9).

Step down 305 mm, front leg force measured: 198% of body mass (Figure 10).

After analyzing the results and comparing them to the recommended impact we decided to modify the experiment and retain from the above only stepping down, plus add jumping down with both legs simultaneously. We also increased the step to 385 mm to reach ground forces closer to the 300% achieved by the exercises performed by the authors of the above papers on high-impact exercise.

To create an equivalent of an urban route with a step we used a steady long bench. The vertical distance between the bench and the force platform was 385 mm.

Figure 6. Routes from Packington bridge towards the Regent's Canal sidewalk. London.

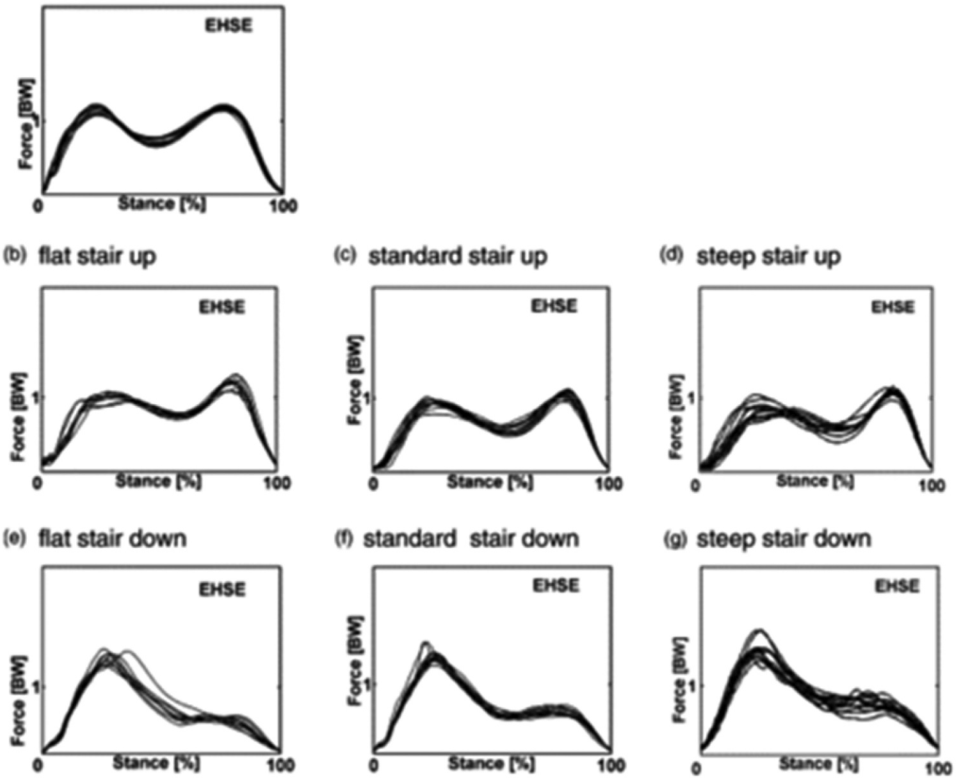
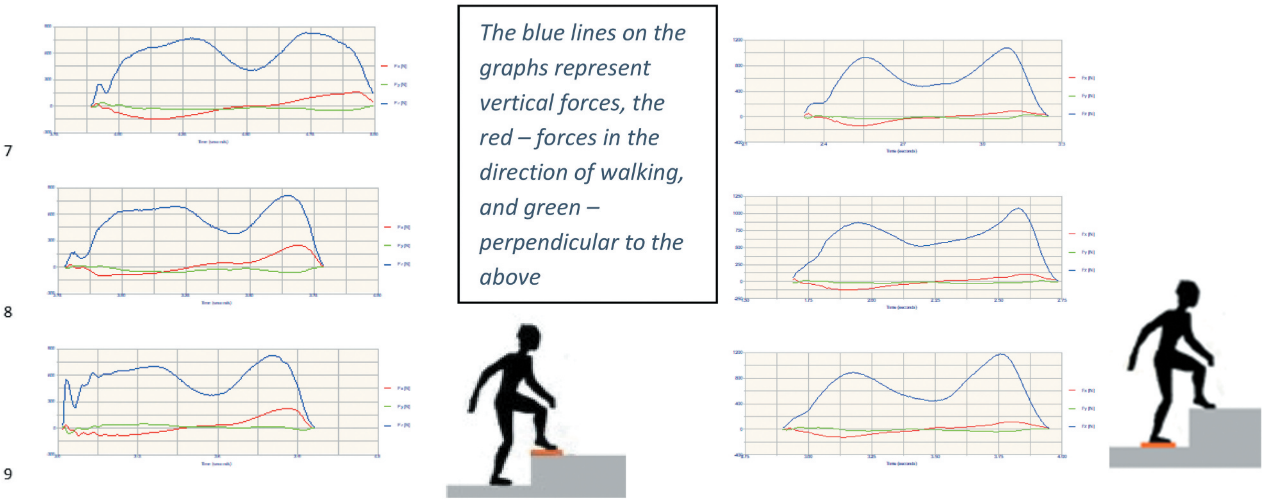


Figure 8. Ground reaction forces when walking horizontally and using stairs (Stacoff *et al*. 2005).



The blue lines on the graphs represent vertical forces, the red – forces in the direction of walking, and green – perpendicular to the above

Figure 9. Step up, measurement: front leg and back leg. The character or load dynamics.

In the first part of the experiment, we asked 17 subjects to walk from one end of the bench to another, step down, and continue walking.

In the second part of the experiment we asked subjects to walk along the bench, jump down and then continue walking (Figure 11).

The ground reaction forces created by these maneuvers were determined using a force platform and loading histories in 3 dimensions: vertical, in the direction of walking and perpendicular to the direction of walking. We recorded the subject's weight (as measured by the force platform) and height (self-reported).

Results

Over the 17 subjects, the average maximum vertical force when stepping down 385 mm was 2.72 ± 0.242 times weight (95% Confidence Interval) (2.78 for male, 2.66 female) rising from 0 to maximum in 0.1 sec, and when jumping down 4.31 ± 0.433 times weight (4.66 male, 3.92 female) rising from 0 to maximum in 0.15 sec.

All subjects had various gaits, but in most cases we can see another smooth peak after landing, namely when subjects pushed themselves off the platform.

When jumping, vertical reaction forces showed a steeper rise and a sharper peak in comparison with stepping down (Figure 12). All 17 jumping subjects

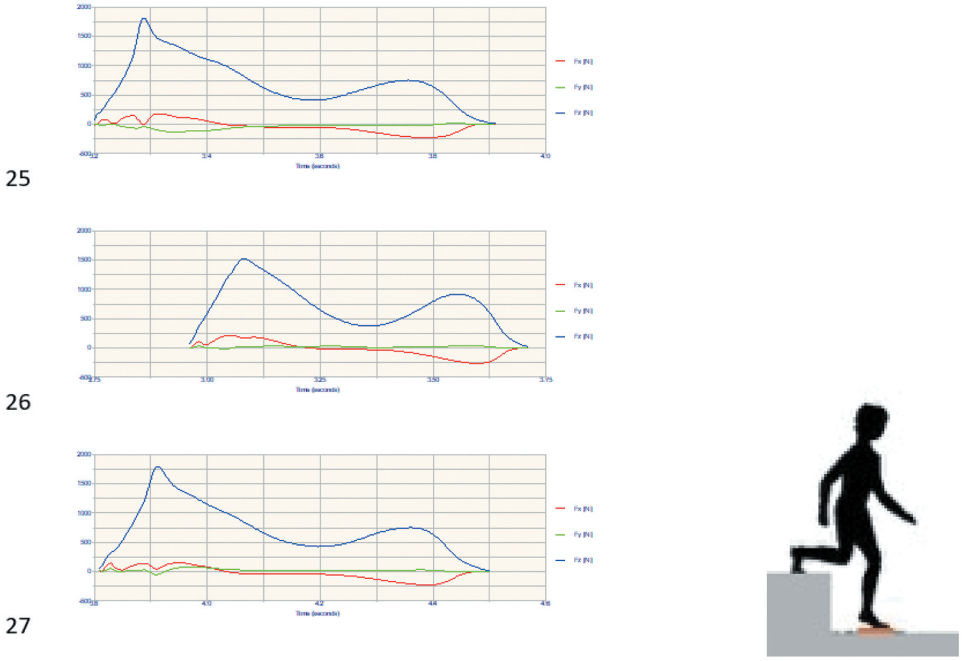


Figure 10. Step down, measurement: front leg. The character or load dynamics.

Figure 11. Jump down on force platform.

had a smaller peak just before the main one associated with the two legs touching the ground at slightly different times. While landing they also experienced several peaks of horizontal forces up to 90 N.

Discussion

Taking into account that an increase in bone density is a response to the magnitude of dynamic load, rather than the number of repetitions in one session and alternating loads with rest increases the effect (Umemura *et al.* 1997, Kemper *et al.* 2000) the design of the Urban Environment appears to be a perfect opportunity to address the bone health problem at the population level. In combination, the literature review, laboratory and field experiments allow us to estimate the potential positive effect of inclusion of high steps into the urban environment on the population's bone health.

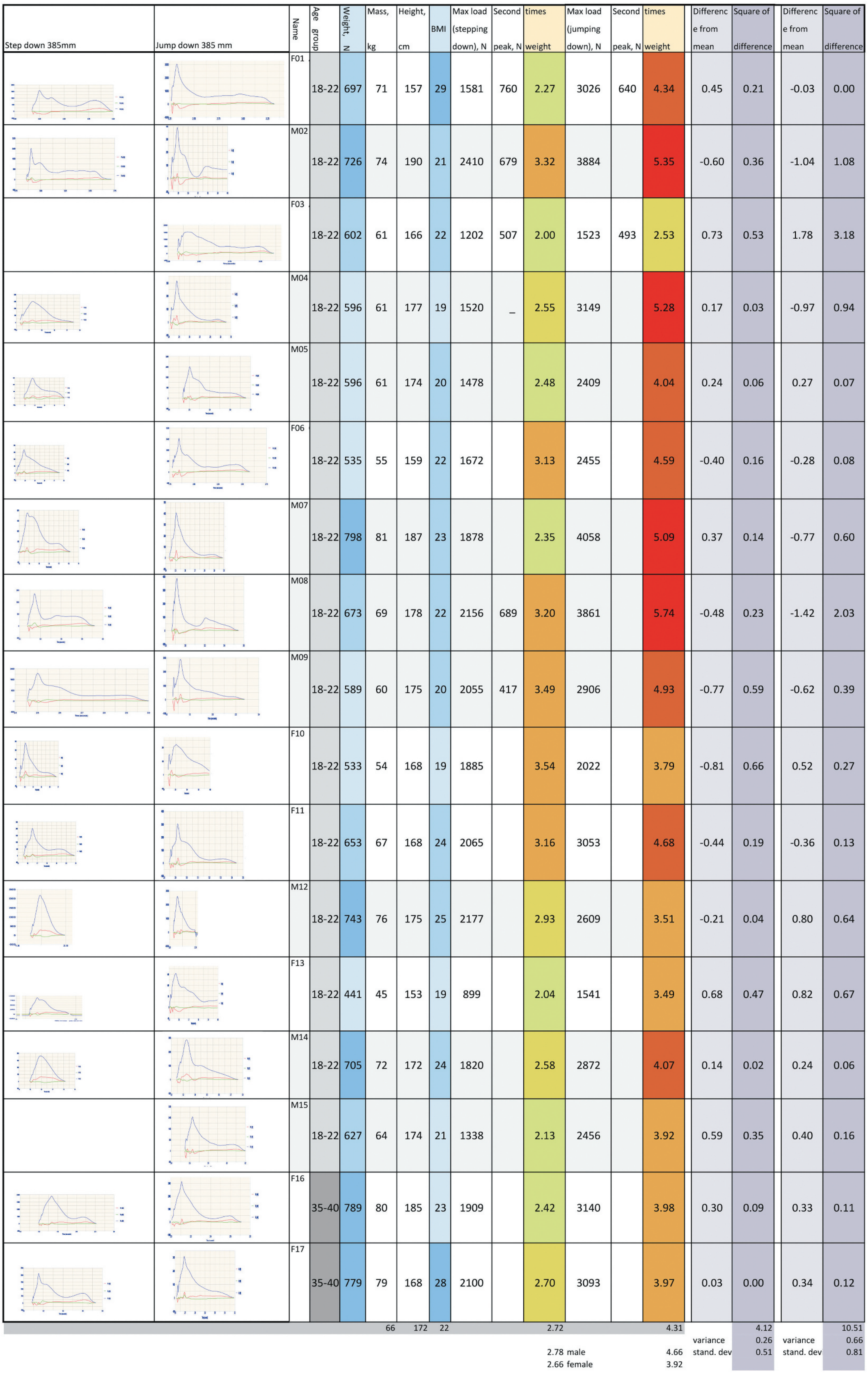
Estimate of the effect of an 'active urbanism' environment on a person across the lifespan

To illustrate the possible effect of intervention over a longer time span, we created the graph below for femoral neck areal mineral density changes through life (Figure 13).

Horizontal line D represents the cutoff line for osteoporosis, as defined by the World Health Organization (Sözen *et al.* 2017), which for the femoral neck stands at 1.035-(0.134*2.5) = 0.698 g/cm^2.

Scenario A: Femoral neck areal mineral density of an average European rises to 1.035 by the early 20s and after 30 starts to decline, reaching the osteoporotic cutoff at the age of 96 years. Individual cases have a normal distribution around 96 years old and, in some cases, this cutoff is reached as early as 45 years, while the other side of the distribution is limited by life expectancy.

Scenario B. Estimated change of femoral neck areal density of a subject starting to use 'Active Urbanism' at 25, after reaching his Peak Bone Density age. According to multiple studies, the more the loadings on bones are spread out in time, the better the osteogenic response they produce (Karl Karlsson and Erik Rosengren 2012, Srinivasan *et al.* 2015). According to the Nottingham experiment middle-aged adults performing 6300 jumps over a period of 5 months increased their bone mass by 2.8% (Bassey *et al.* 1998). This number of jumps can be achieved by jumping twice a day, for example on the way to and from work. If we assume that the Nottingham results can be projected on a longer timespan: starting from age 25 we added 2.8% to curve A for every 10-year period. By the age of 65 years the extra bone density



Step down 385mm	Jump down 385 mm	Name	Age group	Weight, N	Mass, kg	Height, cm	BMI	Max load (stepping down), N	Second peak, N	times weight	Max load (jumping down), N	Second peak, N	times weight	Differenc e from mean	Square of difference	Differenc e from mean	Square of difference
		F01	18-22	697	71	157	29	1581	760	2.27	3026	640	4.34	0.45	0.21	-0.03	0.00
		M02	18-22	726	74	190	21	2410	679	3.32	3884		5.35	-0.60	0.36	-1.04	1.08
		F03	18-22	602	61	166	22	1202	507	2.00	1523	493	2.53	0.73	0.53	1.78	3.18
		M04	18-22	596	61	177	19	1520	_	2.55	3149		5.28	0.17	0.03	-0.97	0.94
		M05	18-22	596	61	174	20	1478		2.48	2409		4.04	0.24	0.06	0.27	0.07
		F06	18-22	535	55	159	22	1672		3.13	2455		4.59	-0.40	0.16	-0.28	0.08
		M07	18-22	798	81	187	23	1878		2.35	4058		5.09	0.37	0.14	-0.77	0.60
		M08	18-22	673	69	178	22	2156	689	3.20	3861		5.74	-0.48	0.23	-1.42	2.03
		M09	18-22	589	60	175	20	2055	417	3.49	2906		4.93	-0.77	0.59	-0.62	0.39
		F10	18-22	533	54	168	19	1885		3.54	2022		3.79	-0.81	0.66	0.52	0.27
		F11	18-22	653	67	168	24	2065		3.16	3053		4.68	-0.44	0.19	-0.36	0.13
		M12	18-22	743	76	175	25	2177		2.93	2609		3.51	-0.21	0.04	0.80	0.64
		F13	18-22	441	45	153	19	899		2.04	1541		3.49	0.68	0.47	0.82	0.67
		M14	18-22	705	72	172	24	1820		2.58	2872		4.07	0.14	0.02	0.24	0.06
		M15	18-22	627	64	174	21	1338		2.13	2456		3.92	0.59	0.35	0.40	0.16
		F16	35-40	789	80	185	23	1909		2.42	3140		3.98	0.30	0.09	0.33	0.11
		F17	35-40	779	79	168	28	2100		2.70	3093		3.97	0.03	0.00	0.34	0.12
					66	172	22			2.72			4.31		4.12		10.51
														variance	0.26	variance	0.66
										2.78 male			4.66	stand. dev	0.51	stand. dev	0.81
										2.66 female			3.92				

Figure 12. Forces in 3 dimensions from stepping down and jumping down 385 mm.

would add up to 11.2%. This is a modest estimate comparing to the results of the Malmö cross-sectional study, which showed that women 38–64 years old who stayed active had 50% higher cortical Bone Mass than the inactive control group by the age of 65 (Jónsson *et al.* 1992).

The Leicester study showed a 0.7% increase of Bone Mineral Density of men aged 65–80 years doing an

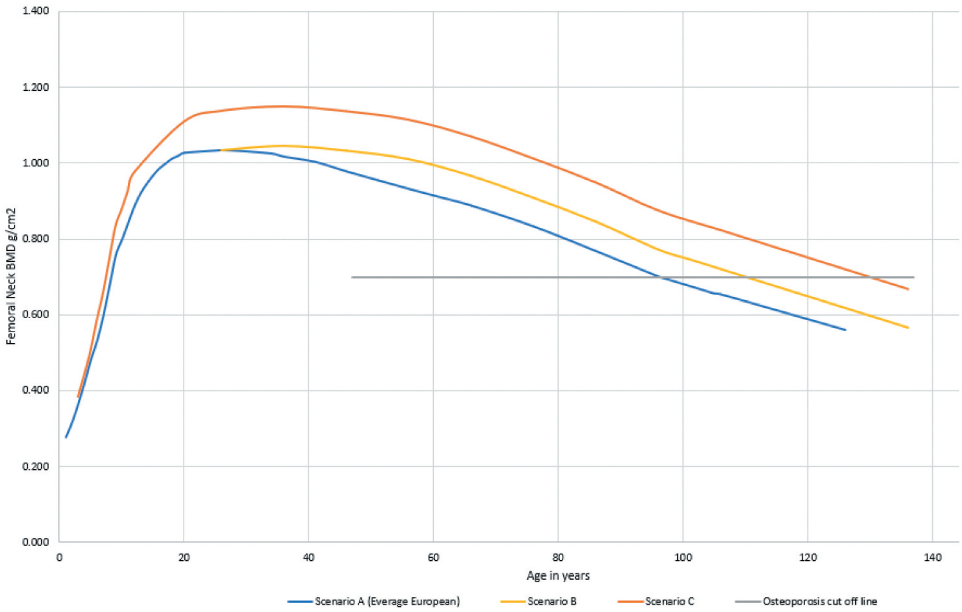


Figure 13. Potential Bone Mass Density changes before and after intervention. Scenario A (Blue) – average European (Gallo *et al.* 2012).Scenario B (Yellow) Potential scenario if an average person stepped down twice a day starting from age 20.Scenario C (Orange) Potential scenario if an average person was born into an 'Active Urbanism' environment, spent extra time as a child playing on a variety of shapes, plus followed scenario B from the age of 20 years.

exercise program, 1.6% higher than the test group which showed a 0.9% decrease. The exercise program consisted of 304 sessions over a year, 50 hops each, making 15,200 hops overall. Assuming it would be the equivalent of 2 hops a day over 21 years – in curve B we added 1.6% in comparison to Curve A in the 21 years from age 65 to 86.

Curve B reaches the osteoporosis cutoff line at 110 years old, shifting the population distribution by 14 years.

Scenario C, estimated change of femoral neck areal density of a subject starting to use 'Active Urbanism' as soon as he starts walking. For the period of life between 1 and 20 years old we added 10% to the growth at this age to scenario B (Karlsson *et al.* 1995, Fuchs *et al.* 2001).

Curve C reaches the osteoporosis cutoff line at 130 years old, 28 years after the current average.

With the current UK life expectancy of 79.3 years for males and 82.9 years for females the numbers above might look theoretical, but we must remember that the age of osteoporosis is distributed both sides of the average, which means that nudging the whole population into high impact exercise would mean greatly extending an active life without fear of fractures for many people (Figure 14).

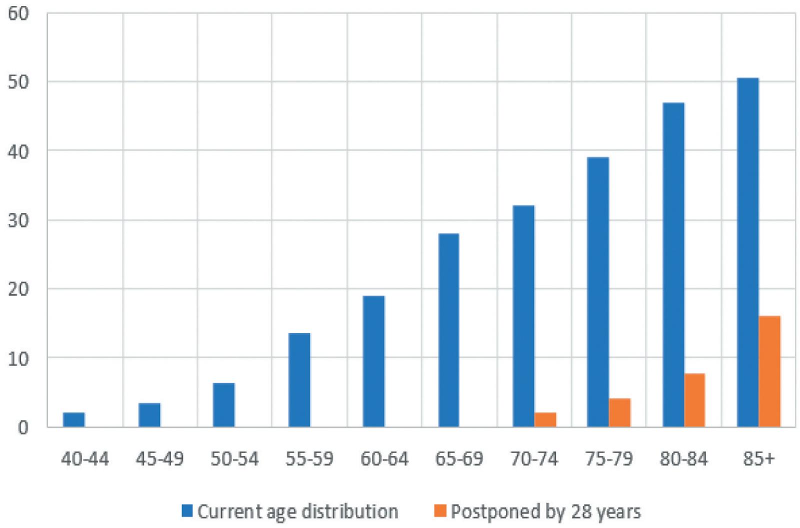


Figure 14. Age distribution of osteoporosis among women now and if postponed by 28 years.

Figure 15. Entrance porch, Edinburgh. Possibility to step down on the side.

Figure 16. Retaining wall following natural terrain, Manchester. Possibility to shorten the route by stepping down.

Figure 17. Artificial elevated landscape, London. Possibility to shorten the route by jumping down.

Design considerations

Providing opportunities for stepping down over 350 mm might appear to involve a lot of construction work, but thousands of potentially useful structures already exist in British cities, unfortunately currently blocked by balustrades (Figures 15–17). Allowing those challenging routes will in no way reduce the accessibility provided by comfortable stairs and ramps; on the contrary, it would reduce the density of crowds and remove the psychological pressure from people moving slower than others.

Another way to allow stepping down over 350 mm in daily walks would be to design part of the stairs for sitting/exercising. The danger of falling in this case can be avoided by clearly visually distinguishing the conventional stairs from the sitting/exercise area (Figs 18–20).

Sculptures and low walls can be often observed in cities being used for walking/stepping on. If the public is formally or informally invited to use them and informed about the bone health benefits, usage

Figure 18. Riverside, Siegen, Germany. Possibility to choose between small and large steps.

Figure 19. Kathmandu, Nepal. Possibility to choose between small and large steps.

Figure 20. Queen Elizabeth Olympic Park. London. Possibility to choose between small and large steps.

Figure 21. Sculpture near St. Paul's Cathedral. London, UK.

might increase (Figure 21). Further research is needed to identify the most attractive and safe ways to incorporate high impact loading opportunities into the city fabric, maximizing use by the population (Figure 22). The practicalities of the concept implementation can be resolved through workshops with practitioners.

Conclusion

Findings showed that changes in the urban environment can have a significant positive effect on the population's bone health if opportunities for high impact exercise are provided and the layout nudges pedestrians into using them fluidly. The laboratory and field experiments showed that loads three times a subject's bodyweight can be reached by jumping/stepping down from the 385 mm step. Risks of fracture and osteoporosis can potentially be delayed by 10 to 20 years or more through urban design interventions, based on extrapolations from theoretical and practical investigations discussed in this paper. To summarize the literature review and the results of the experiment above: including consideration of bone health into the design of the built environment has the potential to improve the health of the general population at all ages. The stepping/jumping down exercises tested above for their effect on bones have other benefits for physical and mental health that will be explored in subsequent papers.

We are aware that our conclusions for urban design need more study and consideration, ideally through presenting our findings to practitioner communities and developing a set of recommendations based on their responses.

Acknowledgments

The authors thank the students and employees of Coimbra University (Portugal) for their participation in the experiments.

Disclosure of potential conflicts of interest

No potential conflict of interest was reported by the author(s).

Funding

Research was approved by the University of Cambridge Faculty of Architecture and History of Art Ethical Committee;Engineering and Physical Sciences Research Council [EP/R513180/1]. Anna Boldina's doctoral research was sponsored by EPSRC DTP. Travel to Portugal to carry out experiments in collaboration with the University of Coimbra was sponsored by the University of Cambridge Kettle's Yard Travel Fund.

Figure 22. Examples of possible incorporation.

Notes on contributors

Anna Boldina BA(Hons), Dip, March After working for 15 years as an Architect/Urban Designer in various practices in London and internationally, Anna is now applying her collected experience to her PhD research in Urban Design/ Sociology/Choice Architecture/Physiology. She is looking for ways to provide opportunities to exercise more effectively during daily pedestrian experiences, whether commutes or walks for pleasure, without extra time spent.

The Martin Centre for Architectural and Urban Studies, Department of Architecture, University of Cambridge, 1-5 Scroope Terrace, Cambridge CB2 1PX, UK

Beatriz Gomes PhD Beatriz is a professor and subdirector on the *Research Unit for Sport and Physical Activity (CIDAF*), Faculty of Sport Sciences and Physical Education, in the University of Coimbra. Her expertise is in biomechanics, kinesiology, biophysics and exercise.

She is also a subdirector of the faculty and a member of Faculty Assembly and the Scientific Committee.

Beatriz is an athlete and reached the final of K-2 500m at the 2012 Summer Olympics in London.

Research Unit for Sport and Physical Activity (CIDAF), Faculty of Sport Sciences and Physical Education,, Estádio Universitário de Coimbra, Pavilion 3, 3040-156 Coimbra, Portugal

Koen Steemers BSc BArch MPhil PhD LLD RIBA ARB Prof Koen is the Professor of Sustainable Design and he has been the Head of Department and Director of Research at the University of Cambridge Department of Architecture. His current research addresses the architectural and urban implications of environmental issues ranging from energy use to human wellbeing. He has over 200 academic publications, including ten books, and worked on numerous large internationally funded research projects related to his area of interest.

The Martin Centre for Architectural and Urban Studies, Department of Architecture, University of Cambridge, 1-5 Scroope Terrace, Cambridge CB2 1PX, UK

ORCID

Anna Boldina http://orcid.org/0000-0003-2601-4438
Beatriz Gomes http://orcid.org/0000-0003-2885-7666
Koen Steemers http://orcid.org/0000-0001-8135-158X

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