Vertical Impact Increase in Middle Age May Explain Idiopathic Weight-Bearing Joint Osteoarthritis

Steven Robbins, MD, Edward Waked, PhD, Nicholas Krouglicof, PhD

ABSTRACT. Robbins S, Waked E, Krouglicof N. Vertical impact increase in middle age may explain idiopathic weight-bearing joint osteoarthritis. Arch Phys Med Rehabil 2001;82: 1673-7.

Objective: To test the hypothesis that ground reaction force increases when a standard stepping task is performed in late middle age.

Design: Consecutive sample.

Setting: Internal medicine practice.

Participants: Thirty-six male patients (age range, 17–72yr) from an internal medicine practice.

Intervention: Subjects performed 20 consecutive footfall impacts onto a force platform while barefoot and while wearing shoes.

Main Outcome Measures: Ground reaction forces were recorded for each footfall.

Results: Impact is positively related to age both when barefoot ($r = .84$, $p < .001$) and when wearing shoes ($r = .71$, $p <$ .001). Impact remains constant until age 50, after which it increases by 13.3% for barefoot subjects. Barefoot impact was significantly lower and less variable than impact when shod (barefoot = 1.18 body weight [BW]; shod = 1.22 BW; $F_{1,5} =$ 169.91, $p < .001$).

Conclusion: An increase in impact force during locomotion was identified that occurs in late middle age, when stability declines and idiopathic weight-bearing joint osteoarthritis develops. Because impact is negatively related to stability, the impact rise is probably caused by postural adjustments to instability resulting from irreversible neurologic decline. This heightened impact may account for the accelerated rate of weight-bearing joint osteoarthritis that begins in late-middle age.

Key Words: Aging; Equilibrium; Osteoarthritis; Rehabilitation; Weight-bearing.

WEIGHT-BEARING JOINT OSTEOARTHRITIS causes joint pain and loss of mobility in many late-middle aged and older individuals[1]; in addition, mortality rates are higher among persons who are less active because of osteoarthritis.[2] Osteoarthritis develops through progressive articular cartilage decline.[3,4] There is a genetic predisposition to osteoarthritis, particularly in the distal interphalangeal joints; however, genetics inadequately explains most cases in which osteoarthritis is restricted to a few joints and asymmetric involvement.[4-6] Its cause is occasionally congenital but is more commonly environmental (external) or idiopathic.[4-6] There is no support for theories that attribute osteoarthritic progression in late middle age to a "natural aging process" or cumulative "wear and tear" from every day activity.[7,8] These hypotheses do not explain why many older people are spared, and they are inconsistent with the results of experimental studies showing that extended normal joint use does not cause deterioration.[9]

The National Health Survey[10] used radiographs to estimate osteoarthritis incidence in the United States from 1971 through 1975[10] in several weight-bearing joints, in relation to age. Incidence in the group aged 35 to 54 years was only slightly higher than it was in young adulthood. It rose in the group aged 55 to 74 years by 800%, 360%, and 150%, for hip, sacroiliac joint, and knee, respectively. Osteoarthritis of hip and sacroiliac joints is mainly idiopathic, whereas in the knee its cause is usually known. These data indicate a marked tendency for osteoarthritis to advance rapidly in weight-bearing joints beginning during the sixth decade of life, whether or not it is idiopathic or from a known cause.

Impulsive skeletal loading below amplitude, causing fracturing (moderate amplitude), provokes osteoarthritis once the load amplitude and total loading cycle thresholds are exceeded. Although the mechanism is unclear, it may be through impact-induced chondrocyte dysfunction, damage to the basal level of cartilage, or trabecular microfracturing of periarticular cancellous bone.[11,12] Regular exposure to hand-tool vibration of moderate amplitude, such as that endured by pneumatic drill operators, causes osteoarthritis of wrist, shoulder, and hands after several years.[12] Exposure to a lesser load amplitude, such as that experienced by users of less vibratory small electric drills, is innocuous. Locomotion can cause weight-bearing joint osteoarthritis in research animals if impact amplitude during locomotion is increased modestly. For example, changing natural, deformable support surfaces to rigid surfaces, which presumably boosts impact during locomotion, causes weight-bearing joint osteoarthritis in sheep with a latency of 2.5 years.[13] It can be provoked in other animals with shorter latency by continuous impulsive joint loading.[14] Impact from sports activities usually does not cause osteoarthritis of weight-bearing joints, except in high-performance runners, who are exposed to greater impact for longer a duration than are slower, noncompetitive runners.[15-17]

Whether or not the cause is idiopathic or is known, all current hypotheses about joint osteoarthritis's cause do not explain why it advances rapidly in all weight-bearing joints in late middle age. The preferred explanation is that a single factor is sufficient to cause osteoarthritis and that factor affects all weight-bearing joints.[18] The one factor of which we are aware that meets these criteria is increased impact during locomotion. We hypothesize that impact during locomotion increases in adults near age 50. We tested this hypothesis by

From the Centre for Studies in Ageing, McGill University (Robbins); Concordia University (Robbins); Divisions of Geriatric Medicine and Experimental Medicine, Montreal General Hospital (Robbins, Waked); and Département de génie de la production automatisée, Université du Québec–École de technologie supérieure (Krouglicof), Montreal, Que, Canada.

Accepted in revised form January 3, 2001.

No commercial party having a direct financial interest in the results of the research supporting this article has or will confer a benefit upon the author(s) or upon any organization with which the author(s) is/are associated.

Reprint requests to Steven Robbins, MD, 800 Rene Levesque W, Ste 1540, Montreal, Que H3B 1X9 Canada, e-mail: *steven.robbins@sympatico.ca.*

0003-9993/01/8212-6262$35.00/0

doi:10.1053/apmr.2001.26255

Table 1: Mean Age and Body Weight for Each Age Group

Age Group	*n*	Age			Body Mass		
		Min	Max	Mean	Min	Max	Mean
<21	6	17	20	18.8	55.9	91.8	76.1
21–30	6	23	30	27.5	61.8	95.4	78.0
31–40	6	32	40	36.5	59.0	107.2	77.9
41–50	6	43	50	46.6	65.4	91.0	81.3
51–60	6	51	60	56.6	61.3	95.0	77.0
>60	6	63	72	66.6	76.6	102.0	86.9

Abbreviations: Min, minimum; Max, maximum.

measuring impact in a random sample of men of different ages performing a standard stepping task.

METHODS

Subjects

Subjects consisted of 36 consecutive patients from an internal medicine practice who met admission criteria regarding age group and mobility. By a priori design, subjects were divided into 6 age groups, with 6 subjects per group. None had conditions affecting their balance and ability to walk, such as severe stability problems and advanced weight-bearing joint osteoarthritis. The mean age and body mass of each age group are listed in table 1.

Force-Moment Platform

A unique force-moment platform was used.[19] It was $500mm^2$ in area and 150mm high. It was capable of measuring peak loads of up to 10,000 newtons, with a resolution of 1 newton for forces, and 0.1Nm for moments. The maximum acquisition and transmission rate for each load sensor was 500 hertz. A high-speed (115kbaud) serial link transmitted data from force-moment platform to host computer, which calculated vertical impact and recorded the data to disk. A graphics-user interface allowed the operator to view the time history of the forces, moments, and center of force.

TESTING PROCEDURE

Written consent was obtained according to guidelines of the Helsinki Declaration. The testing procedure called for subjects to perform 20 consecutive footfall impacts while barefoot and while wearing their own shoes. The details of shoe construction were not recorded—any inference about the effect of specific shoe types is impossible because of the variability of materials and construction methods in the shoes worn. Subjects were required to step forward from a perch, fall to a surface 4.5cm below, land on 1 foot, and remain standing on that foot for several seconds (fig 1). Loss of balance on landing was considered an unsatisfactory trial. Subjects were debriefed after testing to assess their biases regarding the protocol.

Data Analysis

Impact in newtons was recorded by the force-moment platform. Body mass was measured in kilograms and was converted to body weight in newtons by multiplying by $9.81m/s^2$. Impact was expressed relative to body weight (BW; impact [N]/body weight [N]), the customary representation of impact during locomotion. Two-way analysis of variance was performed on impact data. Age group was the between-groups factor, and footwear use (barefoot, footwear) was the within-groups factor. Tukey's honestly significant differences test was used for post hoc testing. Pearson's product-moment correlation coefficient was used to evaluate the relation between age and impact. Alpha level for all tests was .05.

RESULTS

Steady-State Impact

Steady-state impact was achieved in both footwear and barefoot conditions by trial 10, with post hoc testing indicating no

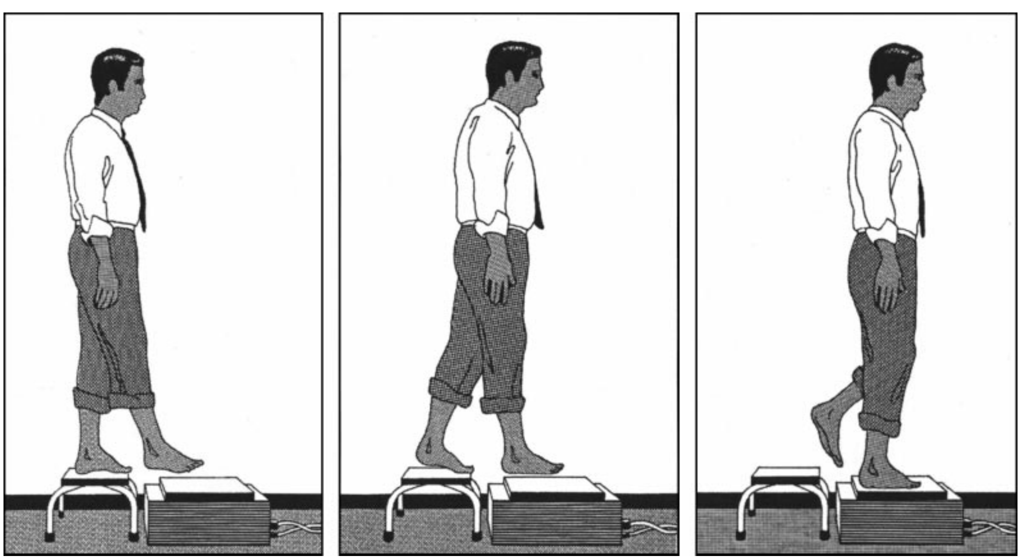

Fig 1. Schematic representation of testing set-up for impact measurement. Subjects stepped down onto the force platform and balanced on 1 foot after contact with the platform. Subjects were tested barefoot, with gaze straight and arms at side on landing.

differences thereafter ($F_{1,35}$ = .33, p = .56). Because the average of trials 11 to 20 was not significantly different from trial 20 for both footwear and barefoot conditions, the last trial was selected for statistical analysis (fig 2).

Impact as a Function of Age Group and Footwear

There was a significant interaction effect between age group and footwear use ($F_{5,25}$ = 10.37, p = .01). Impact varied in relation to age group ($F_{5,25}$ = 30.09, $p < .001$). Post hoc tests indicated no significant difference in impact in the lowest 4 age groups (≤50yr), with means of 1.14, 1.15, 1.14, and 1.16 BW, respectively. Impact did not differ between the 2 highest age groups (>51yr; mean impact 1.30 BW, for both). Both were significantly greater than values for lower age groups (fig 3). Impact was greater when shoes were worn in each of the 4 age groups below 50 years. Footwear and barefoot conditions did not differ significantly for age groups over 50 (fig 3). Impact varied in relation to footwear use. Barefoot impact was significantly lower than impact when shod (barefoot = 1.18 BW, shod = 1.22 BW, $F_{1,5}$ = 169.91, $p < .001$).

Correlation Between Age and Impact

Pearson's product-moment correlation coefficients were computed for age and impact for barefoot and footwear conditions. There was a significant, positive relation between impact and age when barefoot (r = .84, $p < .001$; fig 4) and when wearing shoes (r = .71, $p < .001$; figs 4, 5).

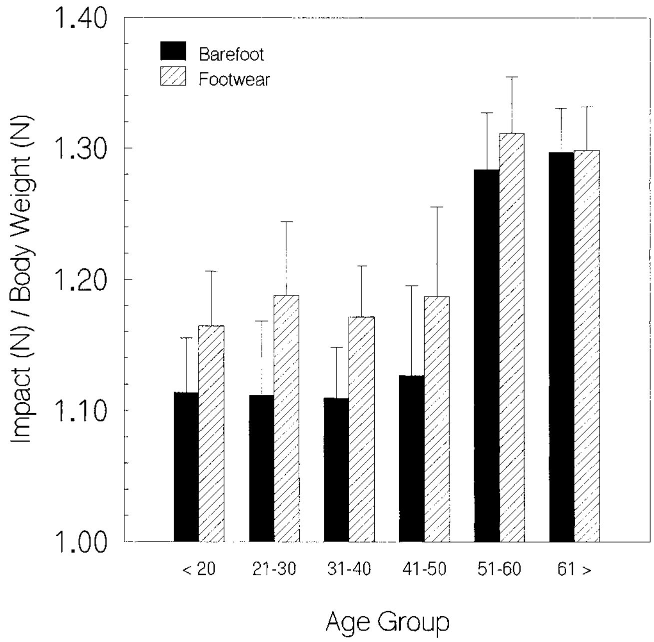

Fig 3. Mean impact for barefoot and footwear conditions as a function of age group.

DISCUSSION

Results indicate that impact when men step remains constant until age 50, at which time it rises 13.3% ($p < .001$) on average for barefoot individuals, and this increase remains relatively unchanged into later years. This is consistent with our hypothesis. The abruptness of the rise seems remarkable, considering that the age of 50 separated barefoot subjects into high and low impact groups without a single exceptional case. This impact upsurge coincides temporally with the development of osteoarthritis of weight-bearing joints of both known and unknown causes.[10] Furthermore, a proven mechanism relates high amplitude repetitive impact, such as occurs when humans walk, to weight-bearing joint osteoarthritis.[12-14] These arguments sug-

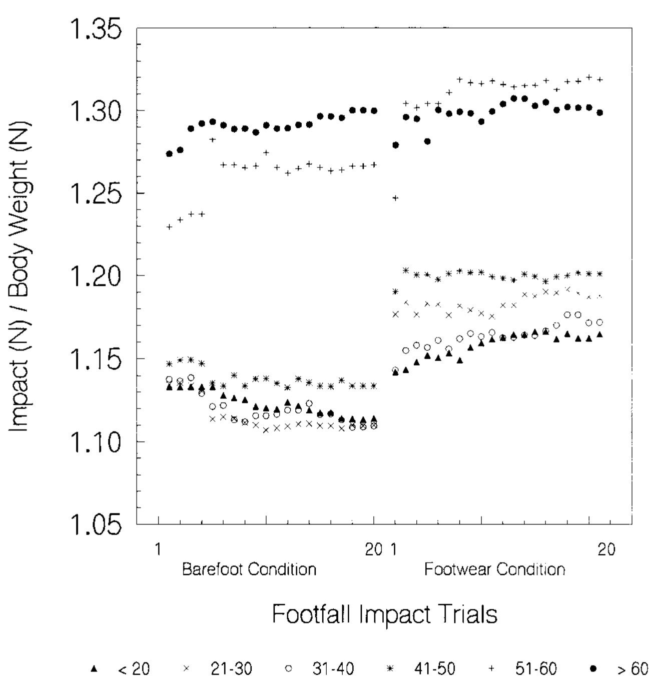

Fig 2. Mean impact for each of the 20 trials as a function of age group, for barefoot and footwear conditions. Impact values were stabilized at trial 10. Trial 20 was used for the statistical analysis.

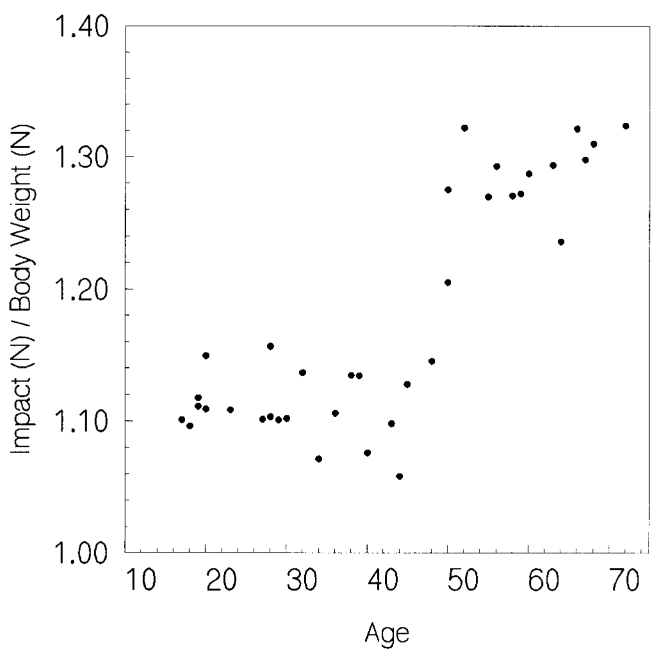

Fig 4. Scatter plot of impact versus age for the barefoot condition. The plot shows complete separation in terms of impact between groups of more and less than 50 years of age, indicating that abruptness of onset and uniformity of impact increase in middle age.

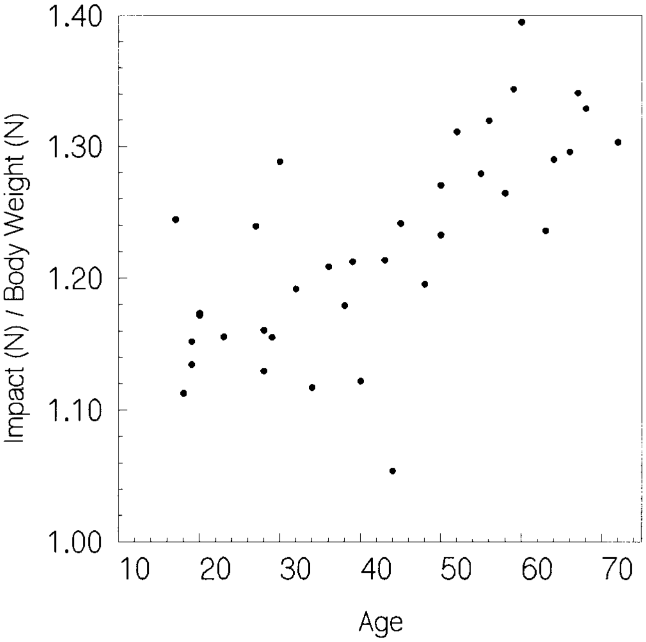

Fig 5. Scatter plot of impact versus age for the footwear condition. Footwear strongly influences stability, hence impact and its influence varies in relation to shoe sole thickness, hardness, and resiliency. Impact was more variable when subjects wore shoes than when barefoot.

gest that the intensified impact associated with aging that we identified is causally related to the rapid weight-bearing joint osteoarthritis advancement that is seen in late middle age.

This rise in impact with aging occurs temporally when stability, as measured by sway measures and incidence of falls, begins to decline in humans. Increased sway is positively related to impact when stepping.[20] This suggests that this impact increase is the result of behavioral responses to instability that are associated with aging.[20] Improving stability should therefore attenuate impact. Many biologic and external factors weaken stability with aging; however, it has been argued that its rapid decline in late middle age is mainly caused by attenuation of foot position sense,[19,21] which probably results from diminished slowly adapting type II mechanoreceptor afferent activity from plantar skin.[21,22] This is not amenable to intervention.

The additional variable of footwear resulted in a similar rise in impact beginning at age 50, with some differences. Comparing shod and barefoot conditions, impact was higher for age groups below 50 years and equivalent for the groups above 50 years. Greater impact by persons less than 50 years with footwear can be explained by the previously reported destabilizing effect of certain footwear sole materials, and the rapid decline in barefoot stability in older groups with its resulting effects on impact.[23] Many subjects of all age groups wore soft-soled walking shoes or athletic footwear. Such shoes substantially impair stability in all humans.[23] No difference in impact in persons above and below 50 years is explained by the additional factor of rapid decline in barefoot stability in older humans.[23]

In view of the relation between impact and stability, interventions known to improve stability in older age groups may delay onset and slow the advancement of weight-bearing joint osteoarthritis by moderating impact. Two methods are of particular interest. Improvement in physical strength and endurance in older people is associated with fewer falls and decreased sway.[24,25] Also, as previously mentioned, footwear with relatively soft and resilient soles, such as found with most athletic and walking shoes, substantially destabilize older people, thereby amplifying impact during locomotion.[23,25-27] Improving the physical fitness of older people and using more optimal footwear may be helpful in moderating impact.

Persons familiar with footwear advertising that claims impact is cushioned by abundant soft sole material might think that the use of thin and firm-soled shoes to improve stability might be counterproductive in moderating impact. However, the literature unequivocally indicates that soft sole materials fail to absorb impact.[27-30] For example, when a series of shoes, which vary only in terms of sole material, were tested by running subjects, the highest impact recorded was with the softest soles.[29] Progress has been made in sole material science. A recent report[22] compared the effect of novel low-resiliency materials with high-resiliency materials typical of those used in all running shoes and in many walking shoes. Low-resiliency soles provided comfort equal to soft-resilient soles, but rather than impairing stability, they were responsible for the lowest sway measures ever recorded in humans in that laboratory.[22] Shoes with low-resiliency soles may lower impact during locomotion in all age groups.

This report is limited in certain respects. A stepping task was considered representative of normal locomotion in all its forms. This introduced error, because impact when stepping is similar to the impact when gymnasts land or when running.[28,29] The sample size, which might be considered relatively small, is accounted for by the statistical method we used. Sampling through consecutive patients might not have been perfectly random. Finally, the physical activity levels between age groups were not considered. Consequently, the impact increase we explained by a decline in plantar tactile sensibility may partly result from augmented impact that is associated with instability related to the lower levels of physical activity in older groups.

CONCLUSION

This report is the first to identify that a sharp increase in impact forces during locomotion occurs at approximately age 50. It is probably the result of postural adjustments from instability caused by a decline in plantar tactile sensibility that is inherent with aging. These results suggest that improving stability in older groups may have a moderating effect on impact forces. This may delay the beginning of, or slow the progression, of weight-bearing joint osteoarthritis. Low levels of physical strength, and footwear with resilient soles, are of particular interest because they upset stability, affect many older people, and are amenable to intervention. Less morbidity from dysfunctional and painful joints and the extended life expectancy that result from improved mobility are potential benefits to older people.

References

1. Yelin E, Lubeck D, Holman H, Epstein W. The impact of rheumatoid arthritis and osteoarthritis: the activities of patients with rheumatoid arthritis and osteoarthritis compared to controls. J Rheumatol 1987;14:710-7.
2. Lawrence RC, Everett DF, Cornoni-Huntley J, Hochberg MC. Excess mortality and decreased survival in females with osteoarthritis (OA) of the knee. Arthritis Rheum 1987;30:S130.
3. Howell DS, Treadwell BV, Trippel SB. Etiopathogenesis of osteoarthritis. In: Moskowitz RW, Howell DS, Goldberg VM, Mankin HJ, editors. Osteoarthritis: diagnosis and medical/surgical management. 2nd ed. Philadelphia: WB Saunders; 1992. p. 233-52.

4. Rosenbaum RB, Campbell SM, Rosenbaum JT. Osteoarthritis and spondylosis. In: Rosenbaum RB, Campbell SM, Rosenbaum JT, editors. Clinical neurology of rheumatic diseases. Boston: Butterworth-Heinemann; 1996. p 91-134.
5. Felson DT. The epidemiology of knee osteoarthritis: results from the Framingham Osteoarthritis Study. Semin Arthritis Rheum 1990;20(3 Suppl 1):42-50.
6. Felson DT. Osteoarthritis. Rheum Dis Clin North Am 1990;16: 499-512.
7. Lane NE, Bloch DA, Jones HH, Simpson U, Fries JF. Osteoarthritis in the hand: a comparison of handedness and hand use. J Rheumatol 1989;16:637-42.
8. van Saase JL, Vandenbroucke JP, van Romunde LK. Osteoarthritis and obesity in the general population. A relationship calling for an explanation. J Rheumatol 1988;15:1152-8.
9. Hannan MT, Felson DT, Anderson JJ, Naimark A. Habitual physical activity is not associated with knee osteoarthritis: the Framingham study. J Rheumatol 1993;20:704-9.
10. National Center for Health Statistics. Basic data on arthritis, knee, hip, and sacroiliac joints in adults aged 25-74 years, United States 1971-1975. Vital and Health Statistics Series 11, No. 213. Washington (DC): Department of Health, Education and Welfare; 1979. DHEW Publication No. (PHS)79-1661.
11. Sokoloff L. Microcracks in the calcified layer of articular cartilage. Arch Pathol Lab Med 1993;117:191-5.
12. Bovenzi M, Petronio L, DiMarino F. Epidemiological survey of shipyard workers exposed to hand-arm vibrations. Int Arch Occup Environ Health 1980;46:251-66.
13. Radin EL, Orr RB, Kelman JL, Paul IL, Rose RM. Effect of prolonged walking on concrete on the knees of sheep. J Biomech 1982;15:487-92.
14. Serink MT, Nachemson A, Hansson G. The effect of impact loading on rabbit knee joints. Acta Orthop Scand 1977;48:250-62.
15. Lane NE, Michel B, Bjorkengren A, Oehlert J, Shi H, Bloch DA, et al. The risk of osteoarthritis with running and aging: a 5-year longitudinal study. J Rheumatol 1993;20:461-8.
16. Lane NE, Bloch DA, Jones HH, Marshall WH, Wood PD, Fries JF. Long distance running, bone density and osteoarthritis. JAMA 1986;255:1147-51.
17. Marti B, Knobloch M, Tschopp A, Jucker A, Howald H. Is excessive running predictive of degenerative hip disease? Controlled study of former athletes. Br Med J 1989;299:91-3.
18. Bochensky JM, editor. Methods of contemporary thought. New York: Harper Pr; 1968.
19. Robbins SE, Waked EG, McClaran J. Proprioception and stability: foot position sense as a function of age and footwear. Age Ageing 1994;24:67-72.
20. Robbins SE, Waked EG. Balance and vertical impact in sports: role of shoe sole materials. Arch Phys Med Rehabil 1997;78: 463-7.
21. Robbins SE, Waked E, Allard P, McClaran J, Krouglicof N. Foot position awareness in younger and older men: the influence of footwear sole properties. J Amer Giatr Soc 1997;45:61-6.
22. Robbins SE, Waked EG, Krouglicof N. Improving balance. J Am Geriatr Soc 1998;46:1363-70.
23. Robbins SE, Gouw GJ, McClaran J. Shoe sole hardness and thickness influence balance in older men. J Am Geriatr Soc 1992;40:1089-94.
24. Brody EM, Kleban MH, Moss M, Kleban F. Predictors of falls among institutionalized women with Alzheimer's disease. J Am Geriatr Soc 1984;32:887-892.
25. Lichtenstein MJ, Shields SL, Shiavi RG. Exercise and balance in aged women: a pilot controlled clinical trial. Arch Phys Med Rehabil 1989;70:138-43.
26. Robbins S, Waked E, Gouw G, McClaran J. Athletic footwear affects balance in men. Br J Sports Med 1994;28:14-20.
27. Robbins SE, Waked EG, Allard P, McClaran J, Krouglicoff N. Aging in relation to optimization of footwear in older men. J Am Geriatr Soc 1997;45:61-7.
28. McNitt-Gray JL, Yokoi T. The influence of surface characteristics on the impulse characteristics of drop landings. In: Proceedings of the 13th Annual Meeting of the American Society of Biomechanics; 1989 Aug 23-25; Burlington (VT). p 92-3.
29. Nigg B. Factors influencing kinetic and kinematic variables in running. In: Nigg N, editor. Biomechanics of running shoes. Champaign (IL): Human Kinetics; 1986. p 139-60.
30. Frederick EC. Biomechanical consequences of sport shoe design. In: Pandolf KB, editor. Exercise and sports science reviews. New York: Macmillan; 1986. p 375-400.