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Finite-element analysis of the effect of basic hip movements on the mechanical stimulus within a proximal femur

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ABSTRACT

Osteoporosis is a serious and multifactorial disease. The number of people affected with osteoporosis is increasing due to the lengthening of life expectancy. Currently, unlike the genetic, nutritional and hormonal factors that have been the focus of most studies of osteoporosis, mechanical stimuli that potentially can produce an increase in bone strength have not been well studied. Studies suggest that the relationship between the health of the bone and mechanical stimuli occurs through bone adaptive remodeling, which is activated by means of the shear stress transmitted by the interstitial fluid flow. The present work consists of a finite element analysis of a femur to simulate the basic movements of the hip (flexion, extension, abduction, and adduction) to compare the shear stresses in a common zone of fracture and in the critical mechanical strength zones of the femoral head. A comparison of the distribution and magnitude of the shear stresses was performed to estimate the movement that could induce a more rapid adaptive bone remodeling. This study is the first step in the development of a physical therapy for a preventive rehabilitation that helps to prevent patients with low bone mineral density to avoid suffering osteoporosis hip fractures. The finite element model was constructed using a free-access three-dimensional standardized femur obtained from the Instituti Ortopedici Rizzoli, Bologna, Italy. The mechanical properties and the muscular forces were obtained from a specialized bibliography. We conclude that the movements that exhibit a higher mean value and a good shear stress distribution in the femoral neck are hip extension and abduction.

Key words. Finite element analysis. Osteoporosis. Mechanical stimulus. Adaptive bone remodeling. Shear stress.

Análisis por elementos finitos del efecto de los movimientos básicos de la cadera en el estímulo mecánico en el fémur proximal

RESUMEN

La osteoporosis es un padecimiento severo de carácter multifactorial. El número de personas afectadas se incrementa debido al aumento de la expectativa de vida. Variables como la genética, nutrición y balance hormonal han sido ampliamente estudiadas, no así los factores mecánicos que se piensa producen un incremento en la resistencia del hueso en presencia de estímulos mecánicos. Algunos estudios sugieren que existe una relación entre la integridad del hueso y los estímulos mecánicos que ocurren por remodelación adaptativa, misma que es activada por los fluidos intersticiales transmitidos a través de esfuerzos cortantes. En el presente trabajo se desarrolla un estudio por elementos finitos de un fémur, en el cual se simulan los movimientos básicos de la cadera: flexión, extensión, abducción y adducción, con el objeto de comparar los esfuerzos cortantes en zonas donde suelen presentarse fracturas y en las regiones críticas para la resistencia mecánica de la cabeza femoral. La magnitud y la distribución de los esfuerzos cortantes se comparan, para determinar cuál de los movimientos básicos induce más rápidamente la remodelación ósea adaptativa. Este estudio es el primer paso para desarrollar terapias físicas preventivas enfocadas en pacientes con baja densidad mineral ósea, para ayudarlos a prevenir fracturas de cadera por osteoporosis. El modelo de elementos finitos fue construido usando un modelo de fémur tridimensional estandarizado de libre acceso obtenido del Instituti Ortopedici Rizzoli, de Bolonia, Italia. Las propiedades mecánicas se obtuvieron de bibliografías especializadas. Se concluyó que los movimientos que muestran un valor medio más elevado, así como una mejor distribución del esfuerzo cortante en el cuello femoral, son la extensión de la cadera seguido de la abducción.

Palabras clave. *Análisis por elementos finitos. Osteoporosis. Estímulo mecánico. Remodelación ósea adaptativa. Esfuerzos cortantes.*

INTRODUCTION

Osteoporosis is a skeletal disease that is characterized by low bone mass and microarchitectural deterioration, with a resulting increase in bone fragility and, hence, susceptibility to bone fracture.[1] The primary consequences of osteoporosis are fractures of the spine, hip and wrist. The most serious fractures are those of the hip, which contribute substantially to morbidity, mortality and high health care costs. The number of hip fractures worldwide is estimated to rise from 1.7 million in 1990 to 6.3 million in 2050. Most hip fractures occur after a fall, with 80% occurring in women and 90% occur-ring in people 50 years old or older.[2]

The main goal of any treatment for osteoporosis is fracture prevention, which should be achieved through a systematic improvement of the mechanical quality of the bones, thereby covering the main concerns that compromises bone health. The current efforts and investigations on osteoporosis are focused on the study of key factors, including genetic, nutritional, hormonal and mechanical.

Genetic factors regulate the bone race characteristics, but they also control the timing of the maximum density. The peak bone mass at any skeletal site is generally accepted to be attained in both sexes during the mid-thirties.[3] After that age, the progressive loss of small amounts of bone tissue begins. Current strategies for prevention and management of osteoporosis address the importance of optimizing the peak bone mass.[4] The nutritional factors are related to situations that increase or diminish calcium intake according to each specific person's lifestyle. The intake of well-balanced nutrition with high calcium is generally accepted to promote bone health,[5] and the presence of an adequate vitamin D supply represents a key nutrient for bone health that assists in the prevention of osteoporosis.[6] Hormonal factors mainly pertain to estrogens because this hormone helps to fix calcium to the bone. Significant diminution of estrogen levels as a result of physiological menopause or the surgical extirpation of the ovaries causes the rapid loss of bone.[7] The last factor in this brief summary is the mechanical stimulus. Bone is able to respond with growth in the presence of mechanic stimuli.[8] Evidently the most desirable strategy to maintain good bone health would be to avoid a non-desirable fracture scenario through a balance of the four factors mentioned above.

This work belongs to the last branch cited, and, just as the several other research groups around the world performing similar work, we seek to identify the best exercise in terms of increasing bone density among the several possibilities of physical activity. It is well accepted that physical activity is one of the primary determinants of skeletal growth and maintenance;[9-12] unfortunately, there are few supporting studies that examine which forms of exercise best prevent osteoporosis fractures.[13]

The dependence between the mechanical stimulus received by the bone tissue and the resulting bone mineral density is modulated by the adaptive bone remodeling process. In 1881, Roux observed that the adaptation of bone is the result of a quantitative regulating mechanism. He suggested a functional adaptation of the architecture governed by mechanical stimuli through trabecular bone, which is regulated locally by cells.[8] To understand the meaning of "mechanical stimuli", several research studies have been performed in recent years. The theoretical and experimental evidence suggests that osteocytes are activated by shear stresses produced by the interstitial fluid shear stress in the bone matrix next to the canaliculi.[14-18]

However, from a physical perspective, there are several important variables in the description of physical activity that must dramatically alter the mechanical stimuli in a specific zone of the bone, such as muscle forces, muscle directions, muscle insertions, duration of force action, and frequency.

We will develop a finite element model to determine the stress at the femoral neck when it is subject to four loading conditions, each of which corresponds to the four basic movements of the hip joint. We believe that, even in simple hip movements, there should be differences in the magnitude and distribution of shear stress in the weak zones of the femoral neck. We will numerically compare the different magnitudes of shear stress targeted on the femoral neck as a means to develop a site-specific physiotherapy for the femoral neck to induce the strengthening of bone based on the 2006 study by Winters-Stone and Snow, in which the authors stated that bone is able to respond to site-specific exercise.[10]

Our findings are the basis of an ongoing physiotherapy study that is targeted to address the weakest zones of the femoral neck to strengthen it.

The susceptible zones of the femur that we studied were determined by the recurrence of hip fractures in osteoporosis patients and by the results of a review of the studies performed on the femoral neck.[19]

The aim of this study is to compare the distribution and the magnitude of the shear stresses on the femoral neck due to four load cases that correspond to basic hip joint movements (flexion, extension, abduction and adduction) to determine the movement that could induce faster operation of adaptive bone remodeling in three critical zones of the femoral neck.

MATERIAL AND METHODS

The work presented here consists of a finite element analysis of the femoral neck using ANSYS software (ANSYS Incorporated, Canonsburg, PA, USA). For the preprocessing stage, we primarily used the standardized femur, a freely available three-dimensional geometry of a left femur that is available on the Internet though the BEL Repository managed by the Instituti Ortopedici Rizzoli, Bologna, Italy.[20] The choice of the material properties and the type of element used are in agreement with the specialized literature.[21] The femoral neck, which is primarily composed of cancellous bone, was modeled as isotropic bone due to the difficulty of determin-ing the anisotropic axes, as well as acceptable values of their mechanical properties. In the model, we did not consider the small layer of cortical bone that covers the spongy bone of the femoral head, which mainly contributes to the protection of the spongy bone and distributes the body weight over the entire femoral trabecular system. The diaphysis and the distal epiphysis, however, were modeled with orthotropic properties, which were assigned in previously studied finite element models (Figure 1, Table 1). The type of element was solid 92, which is an isoparametric tetrahedron of high order consisting of 10 nodes, with quadratic interpolation functions, which enables the modeling of complex geometries with a high degree of precision in the results.

Table 1. Mechanical properties of the model.

Trabecular bone	Isotropic	
Young modulus (Pa)	1.00E+09	Femoral head
Poisson ratio	0.33	
Density (kg/m^3)	1,650	
Cortical bone	**Orthotropic**	
Young modulus in x (Pa)	1.16E+10	Diaphysis and distal epiphysis
Young modulus in y (Pa)	1.12E+10	
Young modulus in z (Pa)	1.66E+10	
Poisson Ratio xy	0.44	
Poisson Ratio xz	0.44	
Poisson Ratio yz	0.44	
Shear modulus xy (Pa)	4.00E+09	
Shear modulus yz (Pa)	5.00E+09	
Shear modulus xz (Pa)	5.40E+09	
Density (kg/m^3)	1,950	

Taylor, *et al.* 2002.[21]

The mesh size was determined after performing a sensibility study of the model using the same loading conditions from a case study while the mesh size was increased. A finite element model of 114,997 nodes and 72,631 elements was used for this study.

The loading conditions were modeled by considering the magnitude and action of the muscles of the hip, as well as the force insertion point for four different movements of the hip: flexion, extension, abduction and adduction. The magnitude and direction of the muscular forces were obtained from Hip98, a freely available collection of data related to hip loading[22] (Figure 2, Table 2). Finally, to model the boundary conditions of the hip joint, an area of the surface of the femoral head, which we estimated makes contact with the hip, was selected, and its

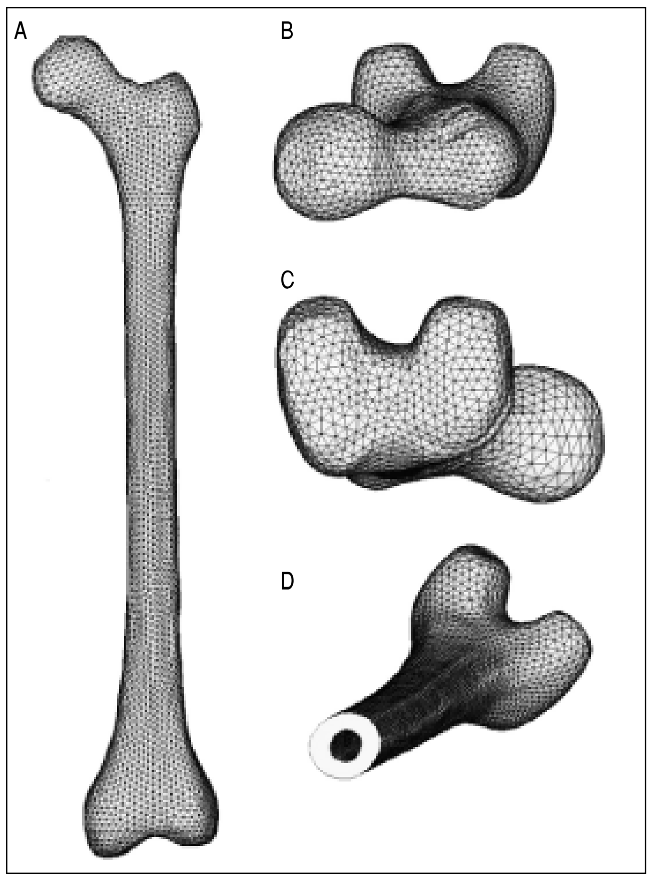

*Figure 1. Finite element model used of the femur. **A.** The whole femur. **B.** Upper view, with the detail of the femoral neck. **C.** Bottom view, with the detail of the condylar region. D. Detail of the medullar canal.*

Table 2. Muscular forces used in the finite element model.

Muscle	Function	X	Y	Z
Iliopsoas	Flexion	78.1	560.3	525.5
Rectus femoris	Flexion	-30.9	26.8	548.7
Sartorius	Flexion	-22.0	-46.7	179.9
Abductor	Extension	-398.3	-29.5	594.0
Hamstring	Extension	-57.0	-9.6	254.8
Semitendinosus	Extension	-114.7	43.3	401.7
Semimembranosus	Extension	-74.9	15.1	271.6
Abductor	Abduction	-398.3	-29.5	594.0
Tensor Fascia Lata	Abduction	-52.9	-84.5	110.6
Adductor	Adduction	-50.1	46.0	70.7
Gracilis	Adduction	-96.1	-33.0	191.9

From Bergmann, *et al.* 2001.[22]

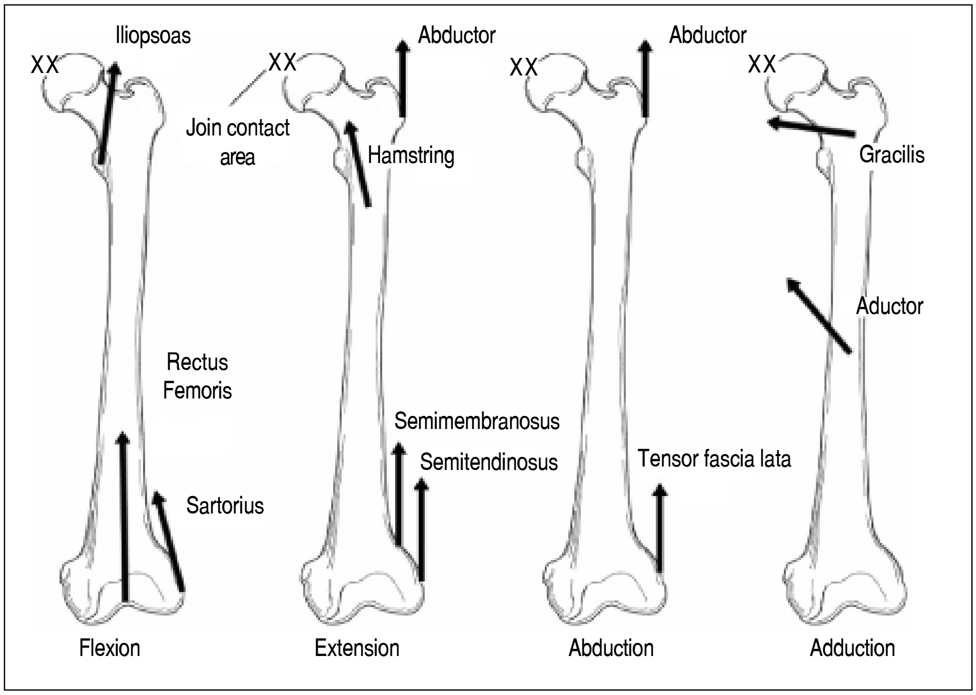

Figure 2. Boundary and loading conditions used for the finite elements models corresponding to the four basic hip movements under study. In every case, the hip joint contact area, marked as XX, was considered to be fixed.

degrees of movement were restricted to zero to model the first instant of muscular action, as shown in figure 2.

RESULTS

Qualitative comparison

To analyze the stress distribution at the most critical zones within the femoral head, we performed two virtual cuts, one in the femoral neck and the other along a mid-sagittal plane of the femoral head. We marked three critical zones that corresponded to those areas where the trabecular patterns crossed each other (Figure 3). We found that extension is the hip joint movement that exhibits the highest stress gradient in both the mid-sagittal cut and the femoral neck. If a higher mechanical stimulus that is characterized by a high shear stress value produces stronger bone tissue, we can say that the stress patterns exhibited in the extension loading case very effectively support both bending and torsional loads (Figure 4). The abduction loading case has the second best stress distribution, followed by the adduction and flexion loading cases.

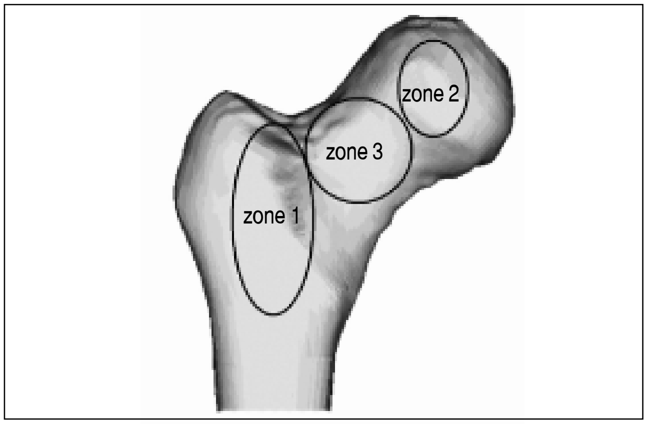

Figure 3. Critical zones of the femur analyzed. The zone 3 is where fractures primarily occur.

Quantitative comparison

A numerical comparison of the mean values of the maximum shear stress was performed. For this purpose, we selected the nodes located in the three critical zones of the femur (Figure 3). The average and standard deviation of the maximum shear stress values were obtained and displayed in a bar chart. Figure 5 shows the comparison of these values. Once again, the extension loading case has the highest mean stress values in the three critical zones, followed by the abduction case. The flexion and adduction loading cases have similar mean stress values in the three critical zones depicted in figure 3.

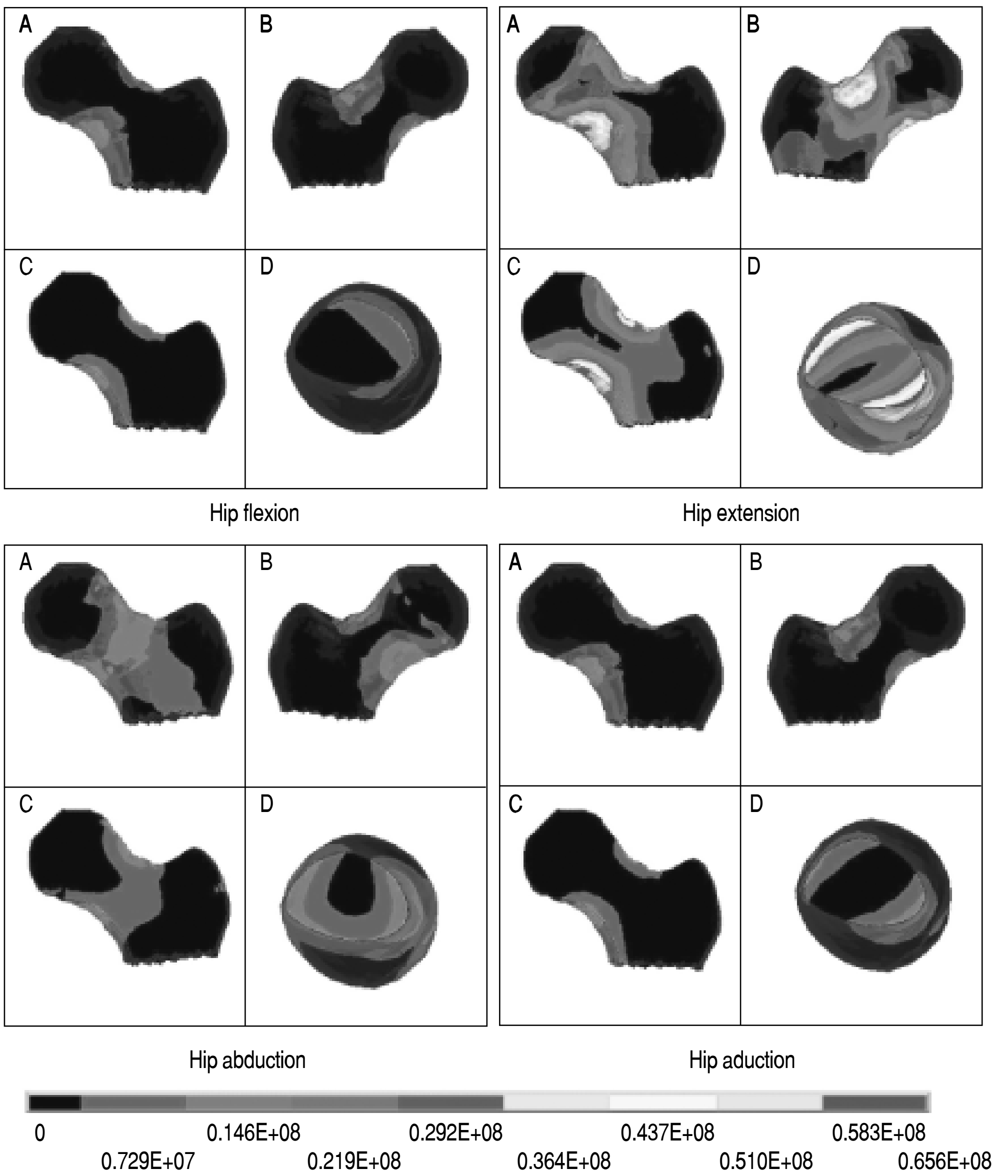

Figure 4. Shear stress distribution for different loading conditions of the femur: hip flexion, hip extension, hip abduction, and hip adduction. A. Posterior view. B. Anterior view. C. Sagittal cut. D. Transversal cut.

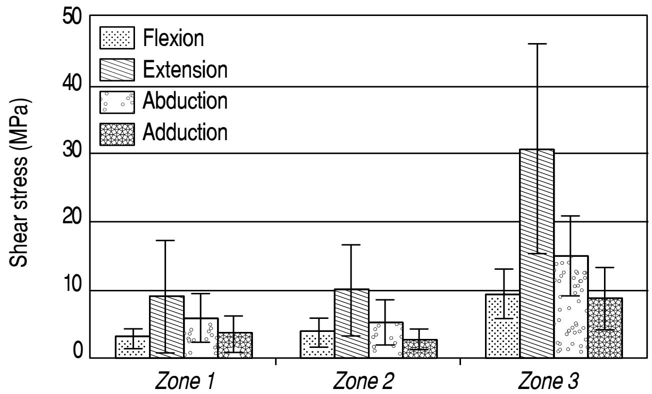

Figure 5. Comparison of the mean values of the maximum shear stresses on the three critical zones for the four femur load cases.

DISCUSSION

In this work, four loading conditions of the femoral neck were simulated. The simulations indicate that the different magnitudes and insertion points of the force simulated produce very different shear stresses in terms of their distribution and magnitude.

The major assumptions of our approach were in the mechanical properties of the model, as we are not considering the spongious bone to be anisotropic; however, other studies suggest that the differences between using isotropic or orthotropic material properties are small: approximately 0.61% in terms of the von Mises stresses and 1.20% in terms of the nodal displacements.[23] Regarding the construction of the geometry, we took advantage of the use of a standardized geometry, which is available in the public domain and has been validated and used widely,[20] as well as the magnitude of the forces.[22]

With respect to the muscle forces, they were simulated as punctual forces because the most important factor is its effect at a distance. Very accurate control of the insertion muscles areas in the bones would have produced an expensive and unnecessarily precise model, which in turn, may lead us to very different conclusions; this technique is widely used in finite element analysis applications to biomechanics; see, for example, Cheung, *et al.*, 2004,[24] and Senalp *et al.,* 2007.[25]

The results of the finite element analysis can help to find a way to induce bone adaptive remodeling in susceptible zones of the femur through the application of shear stresses.

For the four femur-loading conditions simulated, the hypothetical extension movement exhibited a higher value of shear stress in the three critical zones, as well as a good distribution of shear stress. Therefore, we suggest that hip extension must be an important part of a physiotherapy program to increase the bone mineral density of the femoral neck by means of adaptive bone remodeling. The actions of the abductor, semitendinosus and hamstring muscles are decisive in this movement; therefore, that muscle group might be fortified. Abduction movement is second most important in our study; it produces important shear stresses in the three critical zones and also corresponds to the presence of the abduction muscle, which is one of the strongest on the hip. The internal central zone of the femoral neck works under low shear stresses in simulated hip movements; as a result, the remodeling and fortification in this zone are more complicated and slower than other zones of the femoral head, as shown in the sections D of figure 4. In this same figure, an equalized color stress value was used to compare the distribution of shear stress qualitatively. A comparison of sections C indicates that the shear stress distribution during extension and abduction exhibited a better distribution on zone 3, the weakest region of the femoral head, compared with flexion and adduction. This result means that the highest stresses on the femoral head for those movements are in or around the zone previously defined.

Sections D show that the internal central zone of the femoral neck works under low shear stresses in the simulated hip movements; hence, the remodeling and fortification in this zone are more complicated and slower than at the other areas of the femoral head.

The findings discussed above are the basis of an ongoing physiotherapy study that is targeted on the weakest zones of the femoral neck to strengthen it, thereby reducing hip-fracture risk.

Several works focused on rehabilitation found no conclusive link between the bone mineral density on the femoral neck of patients and the therapies of walking and cycling.[9] It is possible that, in those activities, the role of the abductor is not very important; as a result, our work agrees with those research studies because we suggest that, during cycling, the most important movement is likely hip flexion, and the stage of hip extension is assisted by both inertia and gravity. A similar argument can be made with regards to walking and its relationship with extension movement. Walking is commonly advised as a primary activity used to improve bone health; however, no specific description exists on how walking can helpto avoid osteoporosis hip fractures.[26-27]

We recommend that particular attention be paid to extension movement (abductor muscle group) to increase the bone mineral density on the femoral neck.

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