

Hip Contact Stress During Normal and Staircase Walking: The Influence of Acetabular Anteversion Angle and Lateral Coverage of the Acetabulum

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Hip contact stress is considered to be an important biomechanical factor related to development of coxarthrosis. The effect of the lateral coverage of the acetabulum on the hip contact stress has been demonstrated in several studies of hip dysplasia, whereas the effect of the anterior anteversion remains unclear. Therefore, the joint hip contact stress during normal level walking and staircase walking, in normal and dysplastic hips, for small and large acetabular anteversion angle was computed. For small acetabular anteversion angle, the hip contact stress is slightly increased (less than 15%) in staircase walking when compared with normal walking. In hips with large angle of acetabular anteversion, walking downstairs significantly increases the maximal peak contact stress (70% in normal hips and 115% in dysplastic hips) whereas walking upstairs decreases the peak contact stress (4% in normal hips and 34% in dysplastic hips) in comparison to normal walking. Based on the presented results, we suggest that the acetabular anteversion should

be considered in biomechanical evaluation of the hips, especially when the lateral coverage of the acetabulum is small.

Keywords: dysplastic hips, walking downstairs, stair climbing, osteoarthritis, angle of acetabular anteversion, contact pressure

Long-term excessive loading of the hip joint is considered to be important in the development of coxarthrosis (Pauwels, 1976; Brand et al., 2001), which is a frequent reason for functional disability and pain in the elderly (Marks & Allegrante, 2001). The cartilage degeneration may be induced by the direct effect of excessive mechanical loading (Pauwels, 1976; Carter et al., 2004). It has been also proposed that degenerative changes in the hip cartilage may be initiated by alteration of soft tissue accessory structures of the hip (McCarthy et al., 2001). These alterations will significantly influence cartilage mechanical environment subsequently (McCarthy et al., 2001; Ferguson et al., 2000).

It has been shown that the clinical status of the hip and development of coxarthrosis are considerably affected by the contact stress distribution in the hip joint (Brand et al., 2001; Mavčič et al., 2004). In previous theoretical (Ipavec et al., 1999; Genda et al., 2001) and clinical studies (Mavčič et al., 2002), it was shown that hip joint contact stress distribution is significantly influenced by the lateral coverage of the acetabulum, as estimated

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by the center–edge angle of Wiberg ϑ_{CE} (Wiberg, 1939). It is in accordance with a high incidence of coxarthrosis observed in dysplastic hips in which the angle ϑ_{CE} is small (Mavčič et al., 2002). However, the acetabulum is opened not only laterally but also anteriorly (Legal, 1987). In previous studies, the acetabular anteversion was either neglected (Iglič et al., 2002) or fixed for a given patient (Genda et al., 1995).

In addition to the intrinsic geometry of the acetabulum, variation in hip joint resultant force greatly influences hip contact stress (Yoshida et al., 2006). Increased magnitude and variation of the direction of the hip joint resultant force (\mathbf{R}) with respect to the situation during level walking have been observed in staircase walking (Bergmann et al., 1995; Luepingsak et al., 2002). The aim of this study is to evaluate the effect of the acetabular anteversion on hip contact stress distribution during walking upstairs and walking downstairs for hips with various lateral inclinations of the acetabulum. A three-dimensional mathematical model was used to calculate hip joint contact stress.

Methods

The basic assumptions of the mathematical model of the hip joint contact stress distribution used in the present work were described in detail in previous papers (Ipavec et al., 1999; Mavčič et al., 2002); therefore, only basic assumptions of the model are given herein. The model (Ipavec et al., 1999; Mavčič et al., 2002) assumes that the femoral head has a spherical shape and that the acetabulum forms a hemispherical cup. In the unloaded state, the gap between these two rigid spherical surfaces is occupied by a cartilage layer of constant thickness. The cartilage is considered to be an ideally elastic material; that is, the radial strain of the cartilage layer is proportional to the contact stress. Upon loading, the femoral head is moved toward the acetabulum and the cartilage layer is squeezed. Owing to the assumed sphericity of both joint surfaces, strain as well as contact stress in the cartilage layer at any point of the weight-bearing area are proportional to the cosine of the angle between this point and the point of the maximum stress (p_0)—the stress pole (Brinckmann et al., 1981; Greenwald & O'Connor, 1971):

$$p = p_0 \cos \gamma \quad (1)$$

where γ is the angle between the given point and the stress pole. The area of nonzero (positive) contact stress is defined as the weight-bearing area A .

Integration of the contact stress over the weight-bearing area A gives the resultant hip force \mathbf{R} :

$$\int_A p d\mathbf{S} = \mathbf{R} \quad (2)$$

Assuming the cosine stress distribution function (Equation 1), the position of the stress pole and the value of stress at the pole (p_0) are then determined from Equation 2 (Ipavec et al., 1999; Mavčič et al., 2002). If the pole of stress is located inside the weight-bearing area, the peak contact stress p_{max} is equal to p_0 . If the stress pole lies outside the weight-bearing area, the peak contact stress occurs at the point of the weight-bearing area that is closest to the stress pole and can be determined by using Equation 1.

The position of the acetabulum is defined by its lateral inclination given by the center–edge angle of Wiberg (ϑ_{CE} , Figure 1) and by its angle of anteversion (ϑ_{AV} , Figure 1) as defined in Legal (1987). Two values of the center–edge angle that were assessed in the clinical study of hip joint dysplasia (Mavčič et al., 2002) are considered: $\vartheta_{CE} = 31^\circ$ for normal and $\vartheta_{CE} = 13^\circ$ for dysplastic hips. In both hip models, two angles of anteversion were taken: $\vartheta_{AV} = 7^\circ$ and $\vartheta_{AV} = 42^\circ$ for small and large acetabular anteversion, respectively. The angles of acetabular anteversion correspond to the maximal and the minimal values measured in a clinical study (Maruyama et al., 2001). The radius of the articular sphere was taken to be equal to 2.7 cm. The values of the hip joint resultant force (\mathbf{R}) normalized to the body weight (W_B) during normal walking and climbing and descending stairs were taken from Bergmann et al. (Bergmann et al., 2001; Bergmann, 2001).

Results

Figure 1 shows the time dependencies of the peak contact stress normalized to the body weight (p_{max}/W_B) in the hip joint for normal (Figure 1 A, B) and dysplastic hips (Figure 1 C, D) with small (Figure 1 A, C) and large (Figure 1 B, D) acetabular anteversion during the level and staircase walking. Table 1 gives maximal values of the peak contact

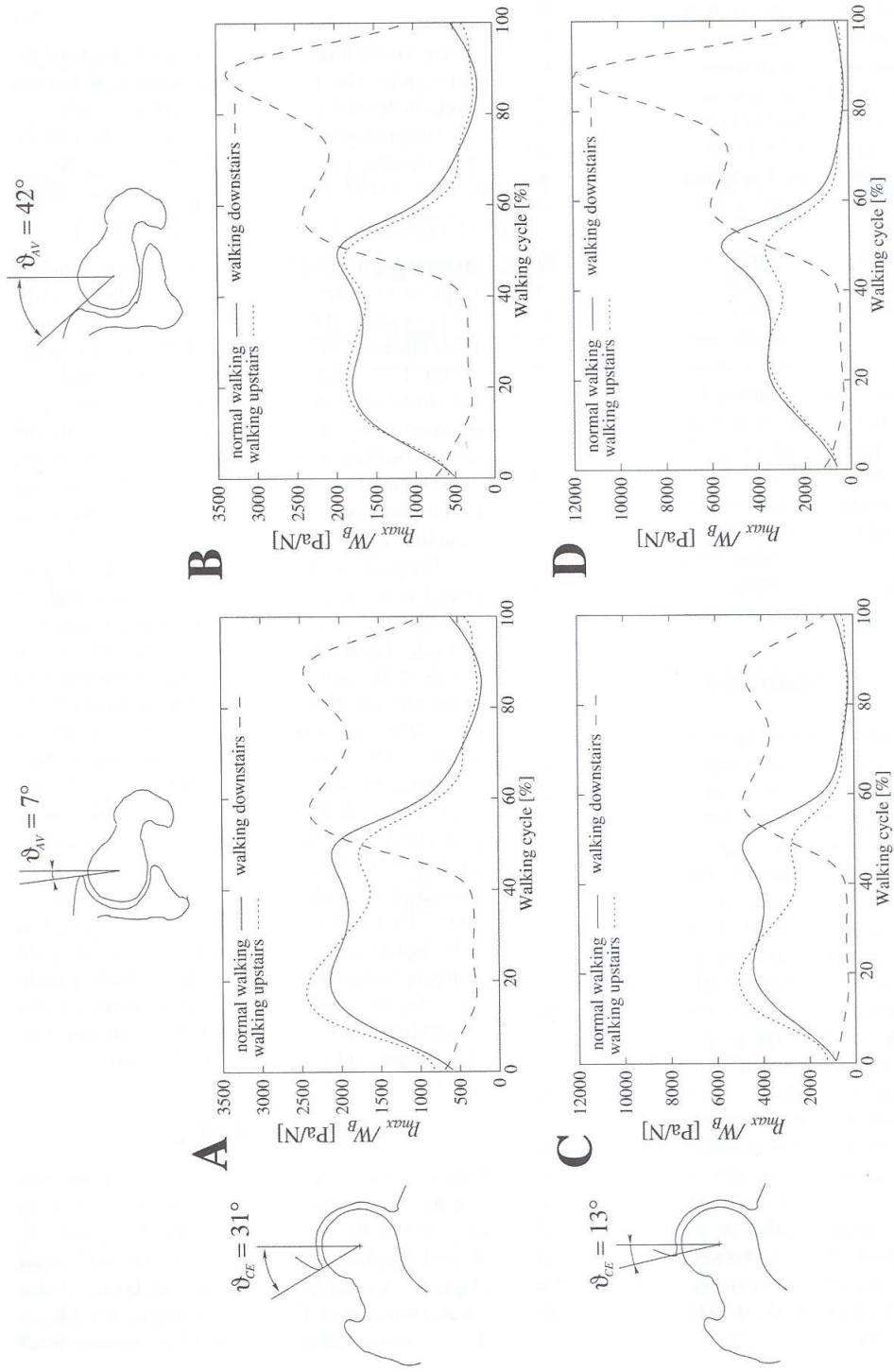


Figure 1 — The time dependencies of the normalized peak contact stress p_{max}/W_B in normal (level) walking, walking upstairs, and walking downstairs for normal ($\varphi_{CE} = 31^\circ$) (A, B) and dysplastic ($\varphi_{CE} = 13^\circ$) hip (C, D) with small ($\varphi_{AV} = 7^\circ$) (A, C) and large ($\varphi_{AV} = 42^\circ$) (B, D) angle of acetabular anteversion. The radius of the articular hemisphere was taken to be $r = 2.7$ cm. Schematic view of the center-edge angles φ_{CE} in the frontal plane of the body (left) and the anteversion angles φ_{AV} in the transversal plane of the body (top) is shown.

Table 1 Maximal Values of Peak Contact Stress Normalized to Body Weight

Anteversion	Hip	p_{max}/W_B in walking				
		Normal (level)	Upstairs		Downstairs	
Small	Normal	2,141 Pa/N	2,439 Pa/N	+13%	2,455 Pa/N	+14%
	Dysplastic	4,864 Pa/N	5,072 Pa/N	+4%	4,846 Pa/N	0%
Large	Normal	1,982 Pa/N	1,900 Pa/N	-4%	3,380 Pa/N	+70%
	Dysplastic	5,569 Pa/N	3,666 Pa/N	-34%	11,985 Pa/N	+115%

stress normalized to the body weight (p_{max}/W_B) in normal (level) walking, walking upstairs, and walking downstairs for normal ($\vartheta_{CE} = 31^\circ$) and dysplastic ($\vartheta_{CE} = 13^\circ$) hip with small ($\vartheta_{AV} = 7^\circ$) and large ($\vartheta_{AV} = 42^\circ$) acetabular anteversion. The relative change of the maximal value of p_{max}/W_B in staircase walking relative to its value in normal (level) walking (measured in percentage) is also shown.

The value of the p_{max}/W_B and the activity that exhibits high hip contact stress depends on the position of the acetabulum (Figure 1). The maximal value of the peak contact stress in dysplastic hips (hips with small lateral coverage of acetabulum) is more than two times larger than its value in normal hips for all three types of walking (Table 1). In hips with small acetabular anteversion angle, the change of the peak contact stress in different types of walking is rather small and almost the same in upstairs and downstairs walking (Table 1). However, there is significant increase in p_{max}/W_B in hips with a large angle of acetabular anteversion during descending stairs. The largest difference in p_{max} with respect to the situation in normal walking was found in dysplastic hips with large acetabular anteversion when walking downstairs where the maximal stress is increased by 115% with respect to its value in normal level walking (Table 1).

Discussion

It has been suggested that elevated hip joint contact stress acting over a longer period may induce degeneration of the articular cartilage, that is, the development of coxarthrosis (Brand et al., 2001; Hadley et al., 1990). In the past, the lateral coverage of the femoral head described by the centre-edge angle of Wiberg (ϑ_{CE}) is considered to be the main parameter that influences the hip contact stress distribution (Legal, 1987; Mavčič et al., 2002; Pauwels, 1976). As in the previous studies (Legal, 1987;

Ipavec et al., 1999), the centre-edge angle ϑ_{CE} was used for characterization of dysplastic hips also in this work and high hip contact stress was reported in these hips (Table 1).

However, as shown in this work, in addition to the lateral coverage of the acetabulum, the angle of acetabular anteversion also considerably influences the contact stress distribution during different types of walking. Figure 1 panels B and D show that a large acetabular anteversion angle considerably increases peak contact stress during downstairs walking in comparison to the other two activities. The value of p_{max}/W_B can be significantly larger during downstairs walking in comparison to normal (level) and upstairs walking, and it reaches 70% in hips with normal ϑ_{CE} and 115% in dysplastic hips with small ϑ_{CE} if the acetabular anteversion angle ϑ_{AV} is large (Table 1).

Recent epidemiologic studies suggest that people who climb stairs very frequently are at higher risk for the development of osteoarthritis (Lau et al., 2000; Luepongsak et al., 2002). If the hypothesis that high contact stress induces arthrosis (Hadley et al., 1990; Mavčič et al., 2002) is correct, results presented in this study suggest that the increased incidence of coxarthrosis in patients who frequently walk upstairs (Lau et al., 2000) is more probably the consequence of walking downstairs (which usually follows previously walking upstairs) in the portion of population with high angle of acetabular anteversion because hip stress during downstairs walking in this population is considerably increased (Figure 1B, D).

It has been shown that hip structures other than cartilage can also play an important role in coxarthrosis development (Klaue et al., 1991). There is increased evidence that tear of the acetabular labrum may be associated with early coxarthrosis (McCarthy et al., 2001). The model presented in this work does not explicitly take into account the

role of acetabular labrum in preventing fluid flow out of the intra-articular space (Ferguson et al., 2000, 2003), although the acetabular labrum tear may be directly connected to the predicted high contact stress in dysplastic hips (Figure 1). As suggested by Pauwels (1976) and confirmed by the same model as used here (Mavčič et al., 2002; Pompe et al., 2003), the contact stress reveals a high gradient close to the acetabular rim in dysplastic hips, with the peak loading at the acetabular rim. We suggest that high loading of acetabular labrum in dysplastic hips may induce its lesion. After the lesion occurs, the sealing properties of the acetabular labrum are altered (Ferguson et al., 2003) and high gradient of contact stress may speed up the cartilage layer consolidation after loading. This process yields to further increases in the contact stress (Ferguson et al., 2003) and increased friction during joint motion. The elevated level of normal and shear stress would lead to progressive cartilage damage consequently (Carter et al., 2004).

It should be stressed that the accuracy of the results given in Figure 1 and Table 1 are limited by several simplifications introduced in the mathematical model for the calculation of contact stress distribution. For example, in the model, the underlying bone in the hip joint was taken to be absolutely rigid whereas deformations of the bone under physiological conditions could change the stress distribution (Bay et al., 1995). The presented model is valid only for the congruent acetabulum, the radial curvature of which is similar to that of femoral head (type II as classified by Klaue et al., 1991). If the acetabulum is shallow and has a radius of curvature significantly different from that of femoral head (type I after Klaue et al., 1991), the adopted cosine stress distribution function (Equation 1) is not valid. Also, further deviations from the spherical shape of the bone surfaces of the femoral head and acetabulum (Rushfeld et al., 1979) change the stress distribution function (Equation 1) and the accuracy of the predicted values of the peak contact stress (Ipavec et al., 1999). In the case of an irregularly curved acetabulum, the geometry of the model should be based on actual geometry taken from CT or NMR scans.

Even a congruent acetabulum may not form a perfect hemisphere in its inferior part. In this case, the contact area may be overestimated by assuming

a complete hemispherical acetabulum. However, the weight-bearing area of the acetabulum lies in its superolateral dome, and the inferior region would not be expected to actually distribute much load (Pauwels, 1976). Therefore, actual underestimation of stress distribution as a result of overestimating contact area would be negligible (Ipavec et al., 1999).

Conclusion

We have shown that the hip contact stress in different types of walking can strongly depend on the angle of acetabular anteversion. If the acetabular anteversion angle is high, hip contact stress during walking downstairs is considerably increased in comparison to its values in normal (level) walking in normal and in dysplastic hips. Based on these results, we suggest that increased contact stress in walking downstairs (but not upstairs) in hips with large acetabular anteversion may be associated with higher incidence of coxarthrosis observed in patients who frequently climb stairs. We conclude that the acetabular anteversion should be taken into account when performing biomechanical analysis of the hip during dynamic activities, especially in dysplastic hips where the contact stress is high (Figure 1 D).

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