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Isolated changes in femoral version do not alter intra-articular contact mechanics in cadaveric hips

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ABSTRACT

Abnormal femoral version is a deformity in the angle between the femoral neck and the transcondylar axis of the knee. Both femoral anteversion and retroversion alter passive and active rotation of the hip and are associated with intra-articular or extra-articular impingement. However, little is known about the effect of abnormal femoral version on intra-articular hip contact stresses. To quantify the effect of femoral version on hip contact stress, five cadaveric pelvis specimens were mechanically tested with a hip-specific Tekscan sensor inserted in the joint space. Specimens were oriented in a heel-strike position and loaded with 1000 N of compressive force. Pressure measurements were recorded by the Tekscan sensor with the femur oriented in 0°, 15°, and 30° of version. At the completion of testing, specimens were locked into place at 0° and post-test CT scans were obtained to register the pressure sensor measurements to the joint anatomy. There were minor changes in contact area (<7%) and translation of the peak contact stress location (8.8 ± 7.6 mm). There was no significant change in peak contact stress ($p = 0.901$) in either the retroverted (0°) or anteverted (30°) conditions relative to normal version (15°) under identical gait-related loading conditions. While abnormalities in patient gait and resultant joint loading caused by femoral version abnormalities may contribute to hip pain, the present findings would suggest that future joint degeneration in hips with version abnormalities are not simply the result of abnormal contact stress induced by joint incongruity due to femoral version abnormalities.

1. Introduction

Femoral version is a measure of anatomy that is commonly quantified as the angle of the femoral neck axis relative to the femoral condyles in an axial plane (Kingsley and Olmsted, 1948). Abnormal femoral version, either anteversion or retroversion, has been found in more than half of patients with hip pain (Lerch et al., 2018). Normal version of the femur has been found to be between 10° and 14° depending on the specific measurement technique utilized (Hartel et al., 2016; Jiang et al., 2015). Relative femoral retroversion (<5°) (Fabricant et al., 2015) is an anatomic deformity where the axis of the femoral neck is rotated posteriorly (Kingsley and Olmsted, 1948), which effectively places the femoral neck closer to the anterior lip of the acetabulum. Similar to the presence of a cam-type bony growth on the femoral neck, a retroverted femur can damage the labrum and articular cartilage (Eckhoff, 1994; Moya et al., 2010; Satpathy et al., 2015) due to impingement during hip flexion. If a patient has both cam-type impingement and femoral retroversion, the combination of these conditions may further decrease impingement-free hip range of motion, thereby exacerbating symptoms of femoroacetabular impingement and causing poorer outcomes after FAI surgery (Fabricant et al., 2015). In contrast, relative femoral anteversion (>25°) is when the head of the femur is pointed more anteriorly relative to the shaft of the femur (Kingsley and Olmsted, 1948). Femoral anteversion has been shown to cause in-toeing gait (MacWilliams et al., 2016) and extra-articular impingement (Siebenrock et al., 2013), including ischiofemoral impingement (Gomez-Hoyos et al., 2016).

The functional effects and symptoms of abnormal femoral version, including pain and aberrant range of motion of the hip, such as increased internal rotation with excessive anteversion or decreased internal rotation associated with femoral retroversion, are addressable with surgical intervention (Buly et al., 2018). In

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contrast, intra-articular factors like increased contact stresses resulting from abnormal version, are much harder to address and contribute to joint degeneration in individuals with these deformities to an unknown degree. A previous cadaveric study evaluated the effects of femoral version on joint contact stress and found that in deep flexion there was an approximate 20% increase in contact stress with femoral retroversion compared to normal femoral version (Satpathy et al., 2015). Yet, despite the overwhelming interest in high-flexion activities associated with impingement, osteoarthritic degeneration related to contact stress is due to repetitions of elevated stress patterns such as those encountered during walking (Anderson et al., 2012, 2011; Segal et al., 2012). Therefore, the objective of this study was to evaluate changes in gait-related hip contact stress associated with different femoral versions.

2. Methods

Five fresh-frozen cadaveric hip specimens were obtained from donors with a mixed sex and health history (University of Iowa Deeded Bodies Program). All soft tissue superficial to the capsule and labrum was carefully excised and the specimens were potted with the femoral shaft oriented vertically in polymethylmethacrylate (PMMA) for mechanical testing. Specimens did not include the distal femur; therefore, the femoral neck was oriented parallel with a flat side of the potting box (as a surrogate for the femoral condyle) to achieve 0° of femoral version. The pelvis was potted with the anterior superior iliac spine and the pubic tubercle oriented in a vertical plane (Wu et al., 2002) and with the pubic symphysis oriented vertically.

For mechanical testing, the specimen was inverted, and the femur was secured to the linear/rotary actuator of an MTS Bionix 858 (MTS Inc. Eden Prairie, MN) via the same aluminum box used for PMMA potting. The pelvis was secured to a compound sine plate mount that oriented the joint in a heel-strike position (16° of flexion, 6° adduction, 6° of external rotation) (Harris et al., 2017). The plate was mounted on an XY stage with dual orthogonal linear bearings attached in series to the load cell (Fig. 1a). The capsule was then removed, and the hip was dislocated using gentle longitudinal traction from the MTS. A calibrated Tekscan 4400 sensor (Rudert et al., 2014) was lubricated with petroleum jelly to decrease shear friction and inserted into the joint. The femur was relocated in the acetabulum, and a 50 N compressive force was applied to secure the Tekscan sensor between the articular surfaces (Fig. 1b).

The MTS actuator was used to rotate the femur externally to simulate 30° of femoral version. This was considered the anteverted position. A ramp load of 1000 N was then applied via the actuator while joint contact pressure data was recorded by the Tekscan sensor. The specimen was then unloaded to 50 N, rotated to simulate 15° of femoral version, and the ramp loading of 1000 N was repeated. Joint contact pressure data was recorded by the Tekscan sensor in this position, which was considered normal femoral version. Again, the specimen was unloaded to 50 N, rotated to 0° of femoral version, and the ramp load of 1000 N

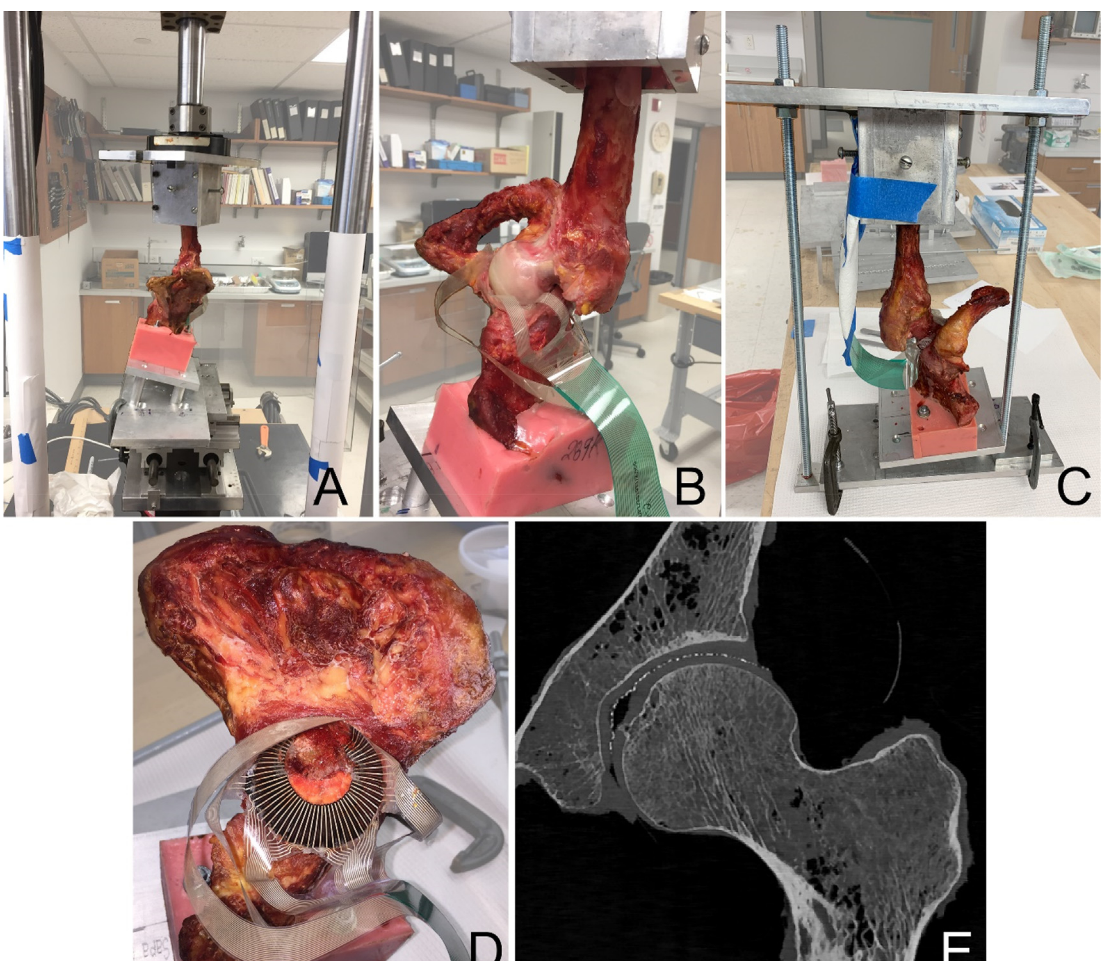

Fig. 1. (a) Specimen in MTS. (b) Femoral head relocated into the acetabulum with the Tekscan sensor in place. (c) Specimen locked with Tekscan sensor in place for transfer to CT scanner. (d) Tekscan sensor position in the acetabulum. (e) Coronal view CT slice with the wires of the Tekscan sensor visible within the joint.

was applied a final time while joint contact pressure data was recorded by the Tekscan sensor. This was considered the retroverted position. The specimen was locked in this loaded position with two threaded rods spanning the upper and lower assemblies (Fig. 1c) so that the testing apparatus could be removed from the MTS in the same orientation as it was tested and transported for CT scanning to confirm sensor location within the joint space (Fig. 1d) (Townsend et al., 2018). The femoral head and acetabular geometry were segmented from the CT scans (Mimics, Materialise, Plymouth MI), and a custom MATLAB (The MathWorks, Natick, MA) algorithm was used to assess the root-mean-square deviation (RMSD) from sphericity (Thomas-Aitken et al., 2019). CT scans were also reformatted to generate a cross-sectional view through the 2o'clock position, and the alpha angle was measured to quantify presence of any cam-type femoral deformity (Scott et al., 2018).

The raw Tekscan sensel values were converted into contact stress values using the previously collected calibration data. Peak contact stress, total contact area, and location of peak contact stress were extracted for each version test on every specimen utilizing a custom script developed in MATLAB. The average, standard deviation, and percent change from the normal version were calculated for these values in all three experimental groups. The distance the location of peak stress moved over the articular surface and the 2D correlation between the contact stress maps between the 0° and 15° positions, the 15° and 30° positions, and the 0° and 30° positions were also calculated to assess differences in stress distribution within the joint associated with femoral version. Repeated measures one-way ANOVA with Tukey's multiple comparisons and a multiplicity adjusted $p < 0.05$ (Prism 8.2.1, GraphPad, San Diego, CA) was used to determine the significance of differences in contact stress and area between the retroverted, normal, and anteverted femur versions.

3. Results

ANOVA indicated no significant differences ($p = 0.901$) between the average peak contact stresses measured in the different femoral versions (anteverted: 4.59 MPa; normal: 4.66 MPa; retroverted: 4.59 MPa) (Table 1). Similarly, there was no significant difference ($p = 0.071$) in the contact area among the different femoral versions (anteverted: 1074 mm^2; normal: 1112 mm^2; retroverted: 1189 mm^2) (Table 2). The pairwise comparison did indicate a statistically significant increase ($p = 0.01$) in contact area with femoral retroversion compared to normal version, however the magnitude of the difference was minor, with only a 7% increase in contact area (Fig. 2). The average translation of the location of peak contact stress was minimal, 3.7 mm between the 0° and 15° femoral version positions and 5.5 mm between the 15° and 30° femoral version positions (Table 3). The correlation between the full contact stress maps was very strong (range 0.91–0.97) for the comparison between the 0° and 15° femoral version positions. The agreement in stress patterns was only slightly reduced when comparing with the 30° version position (average 0.896 for 15°–30° and 0.791 for 0°–30°).

4. Discussion

The goal of this investigation was to directly measure the changes in joint contact stress that are associated with changes in the angle of femoral version. Unlike most previous studies of femoral version focused on impingement, this work focused on heel-strike of gait and used Tekscan sensors to measure real-time contact stress inside cadaveric hip joints. Although the size of the contact patch increased slightly with decreasing femoral version, there was a nominal change in magnitude of peak stress and total contact area associated with femoral version angle. There were

Table 1
Individual peak contact stress data expressed in MPa and as a percentage of the values measured in the normal femoral version orientation. Repeated measures ANOVA indicated no significant difference in peak stress between version groups ($p = 0.901$), and pairwise comparisons between version orientations also indicated insignificant differences.

	Retroversion (0°)		Normal (15°)	Anteversion (30°)	
Specimen	MPa	Percentage of Normal	MPa	MPa	Percentage of Normal
1	3.72	93%	3.99	3.72	93%
2	4.45	98%	4.54	4.45	98%
3	6.29	100%	6.29	4.76	76%
4	4.09	100%	4.09	3.93	96%
5	4.39	100%	4.39	6.10	100%
Average	4.59	98%	4.66	4.59	97%
Std Dev	0.99	3%	0.94	0.94	23%
Pairwise p	0.435 vs normal 0.999 vs anteversion			0.991 vs normal	

Table 2
Individual specimen contact area data expressed in mm^2 and as a percentage of the values measured in the normal femoral version orientation. Repeated measures ANOVA indicated a nearly significant difference in contact area between version groups ($p = 0.071$), and a pairwise comparisons indicated a significant increase in contact area with retroversion compared to normal version.

	Retroversion (0°)		Normal (15°)	Anteversion (30°)	
Specimen	mm^2	Percentage of Normal	mm^2	mm^2	Percentage of Normal
1	1090	107%	1014	984	97%
2	1322	105%	1256	1085	86%
3	809	106%	763	835	110%
4	1402	105%	1330	1326	100%
5	1324	111%	1197	1140	95%
Average	1189	107%	1112	1074	98%
Std Dev	243	2%	228	182	8%
Pairwise p	**0.010 vs normal** 0.130 vs anteversion			0.637 vs normal	

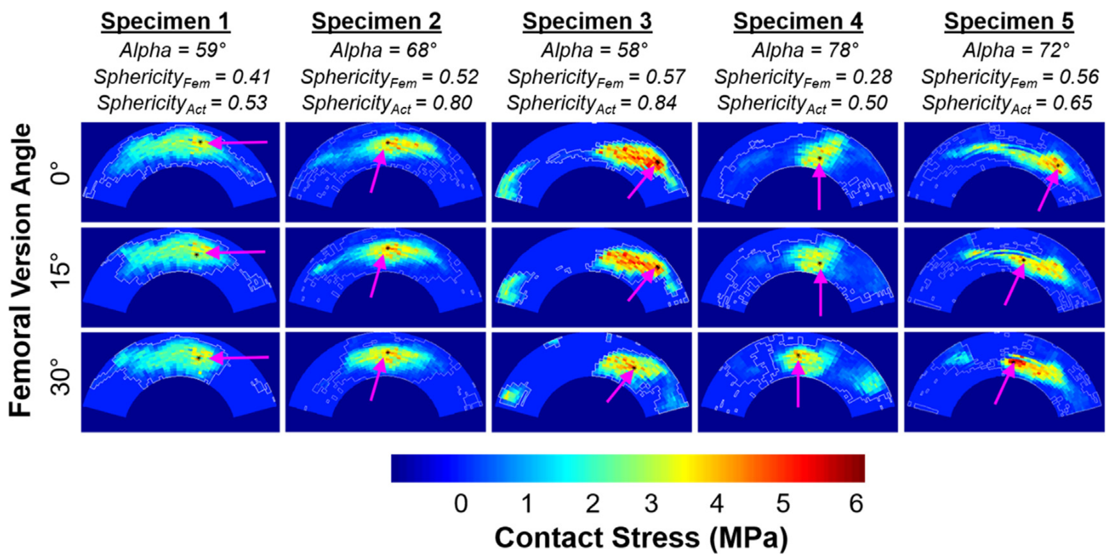

Fig. 2. Composite of Tekscan maps for each specimen in each femoral version testing position. Alpha angles were measured at the 2o'clock position, and the sphericity is the RMSD from a sphere (values of 0 are perfect spheres). The arrows point toward a black asterisk which indicates the location of peak contact stress, and the white outline indicates the area in contact. Anterior is on the right. Specimen 5 had the greatest variation in peak stress magnitude and location, while all other specimens had nearly identical contact stress patterns with varying femoral version.

Table 3

Spatial contact stress data for each individual specimen. Distance is expressed in millimeters over the articular surface between the two indicated version positions. Correlation coefficients are pairwise comparisons between the contact stress maps at the two indicated version positions. Correlation was calculated as $r = \frac{\sum_m \sum_n (A_{mn}-\bar{A})(B_{mn}-\bar{B})}{\sqrt{\left(\sum_m \sum_n (A_{mn}-\bar{A})^2\right)\left(\sum_m \sum_n (B_{mn}-\bar{B})^2\right)}}$, where m and n are the row/column coordinates of each sensel, and A and B are the two contact stress maps being compared.

	Distance (mm)		2D Correlation Coefficient		
Specimen	0° → 15°	15° → 30°	0° → 15°	15° → 30°	0° → 30°
1	3.6	2.0	0.961	0.949	0.898
2	0.0	0.0	0.970	0.947	0.902
3	0.0	10.5	0.953	0.907	0.830
4	0.0	10.4	0.910	0.792	0.543
5	15.0	4.7	0.940	0.887	0.783
Average	3.7	5.5	0.947	0.896	0.791
Std Dev	6.5	4.8	0.023	0.064	0.147

substantial specimen-to-specimen differences in all contact stress measures, yet very close agreement in the full spatial distribution of contact stresses for each femoral version in any given specimen.

We identified only one other biomechanical study investigating the relationship between intra-articular stresses and femoral version (Satpathy et al., 2015). In that work, the authors carefully retained the original femoral version of the specimens and induced version abnormalities as 10-degree offsets from the native version. The associated testing, performed in 90 degrees of hip flexion, indicated 10 degrees of retroversion with internal rotation increased contact stresses by 2–3 MPa and created clear regions of impingement. Those findings differed slightly from our findings that peak stresses changed minimally, likely due to major differences in testing conditions (gait versus deep hip flexion), the occurrence of impingement in the deep flexion experiments, and the wide variety of the femoral version angles tested in the previous work compared to our standardized version angles.

An advantage of the present study was the use of the same cadaveric hip to investigate changes in contact stress related to specific femoral version angles independent of variation in native version between the individual specimens. Another advantage of this work is that the acetabular labrum remained intact during testing, though presence of the Tekscan sensor likely impeded re-establishing a completely normal labral seal. The cadaveric aspect of this work leads to several limitations, notably the constraints provided by the fixed/permitted degrees of freedom in the mechanical testing system and the absence of active and passive soft tissue constraints (capsule and muscles) governing the final orientation of the pelvis relative to the femur during testing. The small number of cadaveric specimens were from individuals older than the typical patient presenting with symptoms related to abnormalities of femoral version. And while rotating the femoral shaft allowed for simulation of femoral version deformities, we were unable to incorporate changes in acetabular anatomy that may accompany naturally occurring version deformities or the effects of that altered acetabular shape on version-related changes in contact stress. Another limitation was utilizing a single static loading configuration instead of the entire gait cycle. Given that patients with femoral version deformities often have labrum/cartilage damage from impingement during high degrees of hip flexion (Eckhoff, 1994; Moya et al., 2010; Satpathy et al., 2015), we chose to investigate heel-strike with the expectation that this highest flexion position during gait would yield the largest changes in contact stress from altered version. Additionally, while individuals with femoral version abnormalities may have abnormal gait patterns (Lee et al., 2013), information about the relationship between femoral version and gait is sparse in young adults with hip pain (Lerch et al., 2019). We therefore elected to use a representative loading pattern that did not make any assumptions of version-related gait changes, such as retroversion-related out-toeing (MacWilliams et al., 2016) and anteversion-related in-toeing (Gelberman et al., 1987).

Based on the data from this cadaveric model of heel-strike, we conclude that abnormal femoral version angles, which primarily served to alter joint congruity in our experimental system, are not a major cause of increases in hip contact stress. Yet, it has been shown that abnormal version is associated with increased joint degeneration (Eckhoff, 1994; Moya et al., 2010; Terjesen et al., 1982; Tonnis and Heinecke, 1999). Given these seemingly conflicting pieces of information, we hypothesize the clinical symptoms and eventual joint degeneration in hips with abnormal version are more likely associated with increases in contact stresses due to gait abnormalities caused by altered moment arms about the hips (MacWilliams et al., 2016), or to additional differences in bony anatomy (i.e. cam deformity (Scott et al., 2018); acetabular shape abnormality (Thomas-Aitken et al., 2019)), than to the femoral version deformity itself. These critical companion variables will be important to include in more comprehensive future mechanical evaluations of the effect of femoral version on hip contact mechanics during gait.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Anderson, D.D., Segal, N.A., Kern, A.M., Nevitt, M.C., Torner, J.C., Lynch, J.A., 2012. Reliability of semiautomated computational methods for estimating tibiofemoral contact stress in the Multicenter Osteoarthritis Study. Comput Math Methods Med 2012, 767469.

Anderson, D.D., Van Hofwegen, C., Marsh, J.L., Brown, T.D., 2011. Is elevated contact stress predictive of post-traumatic osteoarthritis for imprecisely reduced tibial plafond fractures?. J Orthop Res 29, 33–39.

Buly, R.L., Sosa, B.R., Poultsides, L.A., Caldwell, E., Rozbruch, S.R., 2018. Femoral derotation osteotomy in adults for version abnormalities. J Am Acad Orthop Surg 26, e416–e425.

Eckhoff, D.G., 1994. Effect of limb malrotation on malalignment and osteoarthritis. Orthop Clin North Am 25, 405–414.

Fabricant, P.D., Fields, K.G., Taylor, S.A., Magennis, E., Bedi, A., Kelly, B.T., 2015. The effect of femoral and acetabular version on clinical outcomes after arthroscopic femoroacetabular impingement surgery. J Bone Joint Surg Am 97, 537–543.

Gelberman, R.H., Cohen, M.S., Desai, S.S., Griffin, P.P., Salamon, P.B., O'Brien, T.M., 1987. Femoral anteversion: a clinical assessment of idiopathic intoeing gait in children. J Bone Joint Surg Br 69, 75–79.

Gomez-Hoyos, J., Schroder, R., Reddy, M., Palmer, I.J., Martin, H.D., 2016. Femoral neck anteversion and lesser trochanteric retroversion in patients with ischiofemoral impingement: A case-control magnetic resonance imaging study. Arthroscopy 32, 13–18.

Harris, M.D., MacWilliams, B.A., Bo Foreman, K., Peters, C.L., Weiss, J.A., Anderson, A. E., 2017. Higher medially-directed joint reaction forces are a characteristic of dysplastic hips: A comparative study using subject-specific musculoskeletal models. J Biomech 54, 80–87.

Hartel, M.J., Petersik, A., Schmidt, A., Kendoff, D., Nuchtern, J., Rueger, J.M., Lehmann, W., Grossterlinden, L.G., 2016. Determination of femoral neck angle and torsion angle utilizing a novel three-dimensional modeling and analytical technology based on CT datasets. PLoS One 11, e0149480.

Jiang, N., Peng, L., Al-Qwbani, M., Xie, G.P., Yang, Q.M., Chai, Y., Zhang, Q., Yu, B., 2015. Femoral version, neck-shaft angle, and acetabular anteversion in Chinese Han population: a retrospective analysis of 466 healthy adults. Medicine (Baltimore) 94, e891.

Kingsley, P.C., Olmsted, K.L., 1948. A study to determine the angle of anteversion of the neck of the femur. J Bone Joint Surg Am 30, 745–751.

Lee, K.M., Chung, C.Y., Sung, K.H., Kim, T.W., Lee, S.Y., Park, M.S., 2013. Femoral anteversion and tibial torsion only explain 25% of variance in regression analysis of foot progression angle in children with diplegic cerebral palsy. J Neuroeng Rehabil 10, 56.

Lerch, T.D., Eichelberger, P., Baur, H., Schmaranzer, F., Liechti, E.F., Schwab, J.M., Siebenrock, K.A., Tannast, M., 2019. Prevalence and diagnostic accuracy of in-toeing and out-toeing of the foot for patients with abnormal femoral torsion and femoroacetabular impingement: implications for hip arthroscopy and femoral derotation osteotomy. Bone Joint J 101, 1218–1229.

Lerch, T.D., Todorski, I.A.S., Steppacher, S.D., Schmaranzer, F., Werlen, S.F., Siebenrock, K.A., Tannast, M., 2018. Prevalence of Femoral and Acetabular Version Abnormalities in Patients With Symptomatic Hip Disease: A Controlled Study of 538 Hips. Am J Sports Med 46, 122–134.

MacWilliams, B.A., McMulkin, M.L., Davis, R.B., Westberry, D.E., Baird, G.O., Stevens, P.M., 2016. Biomechanical changes associated with femoral derotational osteotomy. Gait Posture 49, 202–206.

Moya, L., Buly, R., Henn, F., Kelly, B., Ma, Y., Molisani, D., 2010. Femoral retroversion in patients with femoroacetabular impingement: a cofactor in the development of hip osteoarthritis. J Bone Joint Surg Br 92-B, 526.

Rudert, M.J., Ellis, B.J., Henak, C.R., Stroud, N.J., Pederson, D.R., Weiss, J.A., Brown, T. D., 2014. A new sensor for measurement of dynamic contact stress in the hip. J Biomech Eng 136, 035001.

Satpathy, J., Kannan, A., Owen, J.R., Wayne, J.S., Hull, J.R., Jiranek, W.A., 2015. Hip contact stress and femoral neck retroversion: a biomechanical study to evaluate implication of femoroacetabular impingement. J Hip Preserv Surg 2, 287–294.

Scott, E.J., Thomas-Aitken, H.D., Glass, N., Westermann, R., Goetz, J.E., Willey, M.C., 2018. Unaddressed cam deformity is associated with elevated joint contact stress after periacetabular osteotomy. J Bone Joint Surg Am 100, e131.

Segal, N.A., Kern, A.M., Anderson, D.D., Niu, J., Lynch, J., Guermazi, A., Torner, J.C., Brown, T.D., Nevitt, M., Multicenter Osteoarthritis Study, G., 2012. Elevated tibiofemoral articular contact stress predicts risk for bone marrow lesions and cartilage damage at 30 months. Osteoarthritis Cartilage 20, 1120-1126

Siebenrock, K.A., Steppacher, S.D., Haefeli, P.C., Schwab, J.M., Tannast, M., 2013. Valgus hip with high antetorsion causes pain through posterior extraarticular FAI. Clin Orthop Relat Res 471, 3774–3780.

Terjesen, T., Benum, P., Anda, S., Svenningsen, S., 1982. Increased femoral anteversion and osteoarthritis of the hip joint. Acta Orthop Scand 53, 571–575.

Thomas-Aitken, H.D., Goetz, J.E., Dibbern, K.N., Westermann, R.W., Willey, M.C., Brown, T.S., 2019. Patient age and hip morphology alter joint mechanics in computational models of patients with hip dysplasia. Clin Orthop Relat Res 477, 1235–1245.

Tonnis, D., Heinecke, A., 1999. Acetabular and femoral anteversion: relationship with osteoarthritis of the hip. J Bone Joint Surg Am 81, 1747–1770.

Townsend, K.C., Thomas-Aitken, H.D., Rudert, M.J., Kern, A.M., Willey, M.C., Anderson, D.D., Goetz, J.E., 2018. Discrete element analysis is a valid method for computing joint contact stress in the hip before and after acetabular fracture. J Biomech 67, 9–17.

Wu, G., Siegler, S., Allard, P., Kirtley, C., Leardini, A., Rosenbaum, D., Whittle, M., D'Lima, D.D., Cristofolini, L., Witte, H., Schmid, O., Stokes, I., 2002. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion-part I: ankle, hip, and spine. J Biomech 35, 543–548.