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Intra-operative femoral condylar stress during arthroscopy: an in vivo biomechanical assessment

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Abstract
Purpose Excessive varus and valgus stress forces during arthroscopy might exceed minimal compressive strength of cancellous bone. In extreme cases, this could lead to post-arthroscopic osteonecrosis. It was our purpose to measure the valgus and varus stress forces during arthroscopy and draw conclusions on the development of osteonecrosis.
Methods On 24 consecutive patients undergoing arthroscopy, the maximum varus and valgus stress forces (N) were measured in vivo using a strain gauge mounted to a leg holder. The forces (N) and contact stresses (kPa) on the femoral condyles were calculated based on the measured acting lateral force at the femur fixation based on the lever principle.
Results The maximum contact stress during varus on the medial condyle was significantly lower in patients with intact meniscus (mean ± standard error of the mean: 243 ± 29 kPa) than in patients with meniscus-deficient knees (520 ± 61 kPa; $P < 0.01$). A similar finding was obtained for the maximum contact stress during valgus on the lateral condyle: 630 ± 72 kPa in patients with intact meniscus compared to 2,173 ± 159 kPa in patients with meniscus-deficient knees ($P < 0.01$). In 19 patients (79%), the maximum contact stress was higher during valgus than during varus. The maximum contact stress on the lateral condyle during valgus was significantly higher for more experienced surgeons ($P = 0.01$).
Conclusion The maximum contact stresses in knees with intact menisci did not exceed the critical threshold of the compressive strength in cancellous bone. However, the maximum contact stresses in meniscus-deficient knees were frequently higher than the threshold. However, these stresses were much lower than those during daily activities and therefore unlikely to lead to post-arthroscopic osteonecrosis.
Level of evidence Diagnostic study, Level II.

Keywords Post-arthroscopic osteonecrosis · Knee arthroscopy · Biomechanics · Joint forces · Varus stress · Valgus stress

Introduction

Spontaneous osteonecrosis of the knee was first described by Ahlbäck et al. [2]. It predominantly occurs in patients over 60 years of age, is three times more common in women than in men and mostly affects the medial femoral condyle.

Spontaneous post-arthroscopic osteonecrosis of the knee has rarely been described [18]. Its aetiology is still under debate [17, 18]. Besides predisposing metabolic factors such as corticosteroid therapy, chronic alcoholism, systemic lupus erythematosus or hemoglobinopathies, a traumatic genesis has been discussed [1, 12].

In theory, microfractures of the subchondral bone lead to a partial bone collapse and allow synovial fluid to infiltrate [18, 25]. Along with this, the intra-osseous pressure of the femoral condyle increases and osteonecrosis might then develop [13, 25].

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Performing varus and valgus stress manoeuvres during arthroscopy could cause high contact stresses on the femoral condyles, eventually leading to post-arthroscopic osteonecrosis of the knee. Considering the fact that post-arthroscopic osteonecrosis has been rarely reported, the contact stresses were not expected to be higher than 1,000 kPa, which is known as minimal compressive strength of cancellous bone [20]. Hence, we aimed at investigating the applied varus and valgus forces during arthroscopy in vivo and at calculating the resultant contact stresses on the femoral condyles.

Materials and methods

Twenty-four consecutive patients undergoing arthroscopic knee surgery, 15 women and 9 men (mean 40 ± 18 years), were included in the present study. In 12 patients the right knee and in another 12 patients the left knee were treated. The body mass index was 25 ± 6 kg/m^2. Arthroscopy was performed for a meniscal lesion ($n = 15$), instability in case of a torn anterior cruciate ligament ($n = 7$), instability for other reasons ($n = 1$) or diagnostically ($n = 1$). The arthroscopy was carried out either by a consultant while the registrar performed the varus and valgus stress manoeuvres ($n = 13$) or by the registrar under assistance of the consultant ($n = 11$).

A custom-made measuring unit was attached to a commercially available knee joint holder (Arthrostress, Sodemsystems, Geneva) without making any changes to the knee joint holder itself. The measuring unit, containing a strain gauge and a thigh constraint device with linear bearing, was able to mechanically differentiate lateral forces from torque, dorsal–ventral and proximal–distal forces. Using this thigh constraint device, only the lateral forces were registered (Fig. 1). The amplified signals were digitized using a data collection system (DAQCard-700 and Measurement Studio, National Instruments, Austin TX). Before the measurements, the system was calibrated with precision load cells. During arthroscopy, the performed varus and valgus stress manoeuvres were noted in relation to the time axis. The measurements were carried out exclusively during the diagnostic arthroscopy.

After positioning the patient on the operating table, the following patient-related distances (in centimetres) were measured using a measuring tape (Fig. 2):

l_f) greater trochanter to knee joint
l_t) knee joint to lateral malleolus
l_h) knee joint holder to knee joint.

On standardized radiographs in anteroposterior view, the following distances (in millimetres) were measured:

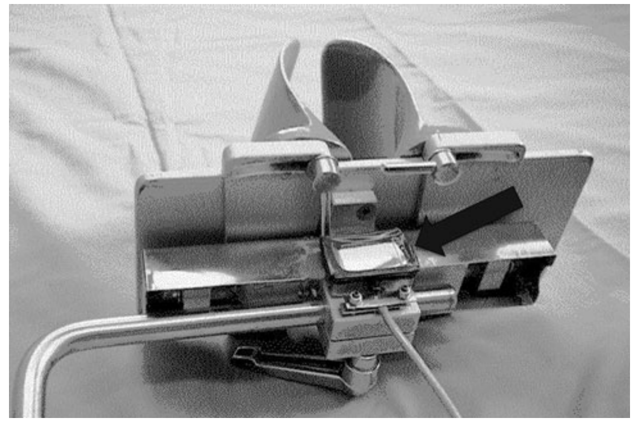

Fig. 1 Illustration of knee joint holder with attached measuring device (marked with *arrow*) on the bottom of the platform

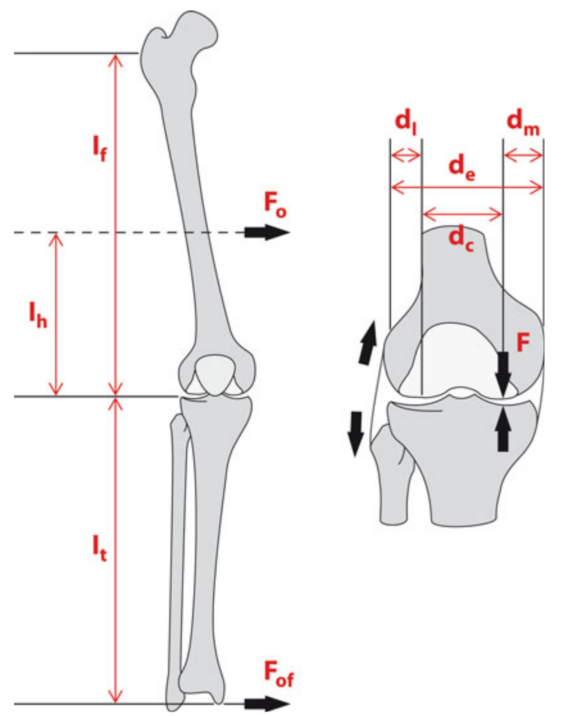

Fig. 2 Morphologic data: Patient-based distances: greater trochanter to knee joint (l_f), knee holder to knee joint (l_h), knee joint to medial malleolus (l_t). Force F_o was measured with the knee holder and used to calculate force F_{of} at the malleolus. Distances measured on radiographs: epicondyle to epicondyle (d_e), condyle to condyle (d_c), lateral epicondyle to lateral condyle (d_l), medial epicondyle to medial condyle (d_m). Force F on the medial/lateral condyle and the tibial plateau was calculated from the measured force during varisation/valgisation

d_c) lateral to medial condyle
d_e) lateral to medial epicondyle
d_l) lateral condyle to lateral epicondyle
d_m) medial condyle to medial epicondyle.

The forces measured on the leg holder were displayed in dependency of the elapsed time during arthroscopy. Negative values indicated varus stress, and positive values valgus stress forces (Fig. 3).

To calculate the forces applied on the medial (F_m, 1) and lateral (F_l, 2) condyles, the following formulae (see Fig. 2 for explanation of variables), according to the lever principle, were used:

$$Fm = \frac{l_t F_0 (l_f - l_h)}{(d_e - d_m)(l_f + l_t)} \quad (1)$$

$$F_l = \frac{l_t F_0 (l_f - l_h)}{(d_e - d_l)(l_f + l_t)} \quad (2)$$

The force applied on the foot (F_{of}, Fig. 2) was calculated using the leg holder force (F_o, Fig. 2) and the distances measured on the leg (Fig. 2). The resultant force was considered to be equivalent to the distracting force on the lateral side of the knee (Fig. 2). The force arising on the condyle (F, Fig. 2) was then again calculated by the lever principle, using the distances measured on the radiographs (Fig. 2).

To calculate the contact stresses, the forces (F_m and F_l) were divided by the contact areas (A_m and A_l). The contact areas were calculated according to Fukubayashi and Kurosawa [5] assuming two clinical scenarios (scenario A—normal loading pattern with intact menisci (+) Men; scenario B—a knee without menisci (−) Men). A linear regression analysis was used to extrapolate the contact areas.

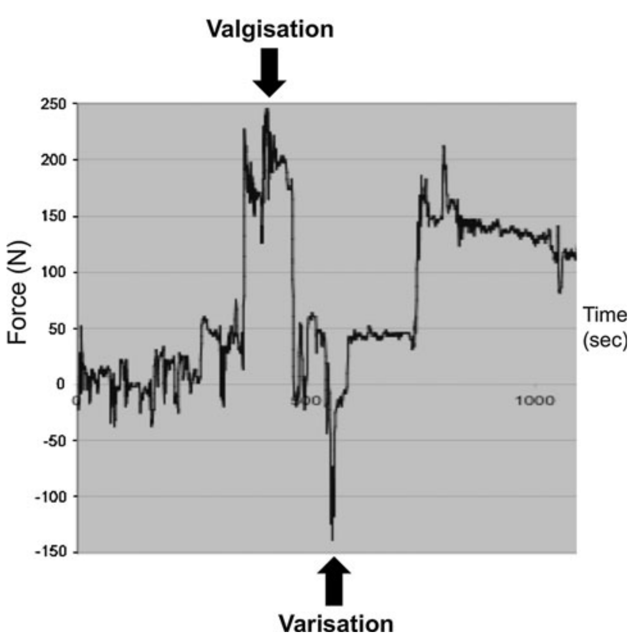

Fig. 3 Example of force graph: force plotted against time for patient 9. The maximum forces reached during valgisation (+) and varisation (−) are marked with *black arrows*

Statistical analysis

The data were checked whether the linear-model assumptions of homoscedasticity and normality were fulfilled [16]. This was the case for all the models fitted. Parametrical tests were used for statistical analysis. The influence of the different patient covariables (sex, age and body mass index) on the calculated contact stresses during varus and valgus manoeuvres was analyzed using multiple linear regression [16]. The differences between scenario A and B and between registrar and consultant (experience of the surgeon) were tested with analysis of variance (ANOVA) [16]. The critical level of statistical significance was set at a P value of 0.05 in both regression and ANOVA.

Results

The mean measured maximum force was 62.8 N (±standard error of the mean: ±8.0 N) during varus stress manoeuvres and 131.7 N (±21.5 N) during valgus stress manoeuvres. The resulting mean force on the femoral condyles was 100.4 N (±12.8 N) and 202.1 N (±33.3 N), respectively.

The mean maximum contact stress on the medial condyle during varus manoeuvre was 243 kPa (±29 kPa) for scenario A and 520 kPa (±61 kPa) for scenario B ($P < 0.001$). The mean maximum contact stress on the lateral condyle during valgus manoeuvre was 630 kPa (±72 kPa) for scenario A and 2,173 N (±159 kPa) for scenario B ($P < 0.001$). In 19 out of 24 patients (79%), the maximum contact stress on the lateral condyle during valgus manoeuvre was higher than the maximum contact stress on the medial condyle during varus manoeuvre.

The maximum contact stresses on the lateral condyle during valgus manoeuvres were higher when arthroscopy was performed by consultants (1,700 ± 225 kPa) than by registrars (1,126 ± 156 kPa; $P < 0.01$). Furthermore, the maximum contact stresses during varus and valgus manoeuvres showed no relation to sex, age or body mass index of patients (n.s.).

Discussion

The most important finding of the present study is that varus and valgus stress manoeuvres during arthroscopy are in the range of contact stresses during daily activities and therefore unlikely to cause osteonecrosis.

The aetiology and pathophysiology of osteonecrosis after arthroscopy is not fully understood. Due to its rarity, only a few case series including a small number of often heterogenous groups of patients have been described [17, 18]. In the most recent study, Bonutti et al. presented a retrospective case series of 19 patients suffering from osteonecrosis of the knee after arthroscopic surgery [3]. In six patients, the development of post-arthroscopic osteonecrosis was attributed to laser treatment, in ten to radiofrequency treatment and in three to microfracturing.

In a cadaveric pig study, Fukuda et al. showed that an intact meniscus is of crucial importance for compressive load transmission within the knee joint [6]. The intact meniscus prevents point loading by distributing the load on a broader contact area. Fukuda et al. further found a two- to fivefold increase in the compressive subchondral stress after meniscectomy [6]. Hence, meniscectomy might play a role in the pathogenesis of post-arthroscopic osteonecrosis of the knee. Prues-Latour et al. presented nine cases of osteonecrosis following arthroscopic meniscectomy [19] and hypothesized that altered load distribution after partial meniscectomy could lead to microtrauma in the subchondral bone and subsequently to osteonecrosis.

Generally, there are two traditional schools of thought regarding the pathogenesis of spontaneous osteonecrosis of the knee [1, 12].

One school believes that altered microcirculation and subsequent subchondral bone ischaemia are the main cause of spontaneous osteonecrosis [4]. Pape et al. hypothesized that in knees with damaged cartilage, arthroscopic fluid permeates into the subchondral bone, causing higher pressure and thus compromising microcirculation [18].

The other school accuses subchondral insufficiency fractures due to altered knee mechanics (e.g. after meniscectomy) as leading cause for development of osteonecrosis after arthroscopy [13, 14, 25].

Taking the second theory into consideration led us to think about possible mechanical triggers during arthroscopic surgery. To our knowledge, the present study is the first to analyze the contact stress on the femoral condyles generated during valgus and varus manoeuvres when performing an arthroscopy. The most important findings of the present study are threefold:

Firstly, our measurements and calculations clearly show that the maximum contact stresses during arthroscopy in knees with intact menisci (scenario A) did not exceed the critical threshold of the compressive strength in cancellous bone. In contrast, the maximum contact stresses in meniscus-deficient knees (scenario B) were frequently higher than the threshold.

Secondly, the calculated contact stress on the lateral condyle was consistently higher during valgus than on the medial condyle during varus.

Thirdly, the higher the level of the surgeon's experience, the higher the resultant contact stress on the femoral condyles.

Based on the first and second finding of the present study, it is unlikely that varus stress and valgus stress manoeuvres during arthroscopy lead to the development of post-arthroscopic osteonecrosis in normal knees. Rohlmann et al. [20] reported that the minimal compressive strength of the cancellous bone in the femoral condyle is approximately 1,000 kPa. Only in meniscus-deficient knees, higher contact stresses and forces than this threshold were found, but these were still low when compared to forces and contact stresses generated during activities of the daily living. Tibiofemoral forces during level walking or downhill walking are known to reach approximately 3.9–8 times body weight, meaning for a body weight of 70 kg forces of 2,730–5,600 N [10, 22, 23]. These values are at least 10 times higher than the forces measured on the condyles during arthroscopy in the present study, which were in the range of 21–824 N.

However, in meniscus-deficient knees, the measured and calculated forces on the femoral condyles were significantly higher, which is in accordance with Fukuda et al. who found that the compressive stress in cadaveric pig knees after meniscectomy was two to four times higher than in meniscus-intact knees. They further highlighted the fact that the compressive stress in the subchondral bone after meniscectomy was significantly influenced by the mechanical frontal plane alignment (varus vs. valgus knees).

If the mechanical varus or valgus stress during arthroscopy would be a decisive factor causing post-arthroscopic osteonecrosis, one could speculate that the incidence of post-arthroscopic osteonecrosis should reflect the force pattern found in our study. The calculated contact stresses were higher for valgus on the lateral femoral condyle than for varus on the medial femoral condyle, which is in contrast to the current literature, where post-arthroscopic osteonecrosis of the knee is more common medially than laterally [17, 18].

In summary, some of our findings are rather paradoxical. Intra-operative contact stress can get rather high, but these rarely exceed the critical threshold of cancellous bone. Hence, the valgus and varus stresses, which occur during arthroscopy, are unlikely to be the cause for post-arthroscopic osteonecrosis. No final conclusions can be drawn out of our findings, but our results clearly demonstrate the need for further studies.

In the future, more sensitive and specific in vivo methodology might be available to investigate loading and stress pattern of the subchondral bone in normals and different pathologies. Using new single or hybrid imaging techniques such as CT-OAM, 3D-MRI or SPECT/CT could be helpful to elucidate the mechanical stress pattern during and after arthroscopy [7–9, 11].

The third finding of the present study is clinically interesting as we showed that applied contact stresses were significantly influenced by the surgeon's experience. Possible explanations might be on one hand greater cautiousness of the less experienced staff. On the other hand, it could be the demand for a better exposure of the joint and better protection of the cartilage that led more experienced staff to ask the registrar to apply greater forces during arthroscopy. We found no other studies dealing with variation in the applied varus and valgus stress forces during in vivo arthroscopy due to the surgeon's experience level. Tashiro et al. found that in an arthroscopy model, the less experienced surgeons applied higher intra-articular forces during joint inspection and probing task than the more experienced ones [21]. This finding seems to be in line with our results, as higher intra-articular forces might be applied during arthroscopy, when the visibility of the medial or lateral compartment is impaired due to less vigorous varus and valgus manoeuvres. Virtual-reality arthroscopic training systems could give younger surgeons valuable feedback on their surgical skills [24]. The training scenario and arthroscopic setting should be as realistic as possible [24]. However, to date, varus/valgus forces applied to the knee joint have not been integrated in any system but could be of interest as visibility of the knee joint during arthroscopic surgery is a key factor for the outcome of surgery.

We are aware that this investigation has several limitations. One could speculate whether the measured forces and calculated contact stresses on the femoral condyles truly reflect the intra-articular stress pattern of the knee joint as the forces and contact stresses have only been indirectly measured and calculated based on Fukubayashi and Nakamura's work [5]. These authors reported tibiofemoral contact areas in a similar clinical scenario for 200, 500 and 1,000 N forces. In addition, they also characterized the tibiofemoral contact areas for patients in intact and meniscus-deficient knees. The size of the tibiofemoral contact area in this study was estimated and not measured for each patient individually. Using this method, variation of mechanical leg alignment as well as the shape of the femoral condyles was not incorporated [6]. Three-dimensionally reconstructed CT images would have provided more accurate information on individual patients' anatomy and contact areas but could not be performed for ethical reasons.

Also, measuring the contact stress directly in the joint would be more accurate but is hardly feasible in vivo. On the other hand, a cadaveric study could also not adequately factor in the effect of ligaments and muscles on the contact stress generated during arthroscopy. However, the results of cadaveric experiments would probably add value to the interpretation of our data.

There are different ways of positioning the patient for arthroscopy. All patients included in this study were positioned equally (supine position, knee fixed in a leg holder and flexed to 60–70 degree). Others perform arthroscopy on a hanging leg, fixed in an electrical or conventional legholder [15]. Hence, we can only conclude on the group of patients positioned supine and with the knee flexed to 60–70 degree and not on patients positioned differently.

Another limitation of the present study was that only maximum contact stresses were analyzed, and the time during which certain force and therefore contact stress was applied might be an important factor causing osteonecrosis.

Conclusion

In spite of the above-mentioned limitations, we believe that there is sufficient evidence to conclude that it is unlikely that varus and valgus stress manoeuvres during arthroscopy cause post-arthroscopic osteonecrosis. Especially, these contact stresses cannot be regarded as the only cause of post-arthroscopic osteonecrosis, which probably has multiple causes and remains unclear. The present study gives an idea of the order of magnitude of the contact stresses caused by varus and valgus manoeuvres during arthroscopy.

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References

1. Aglietti P, Insall JN, Buzzi R, Deschamps G (1983) Idiopathic osteonecrosis of the knee. J Bone Joint Surg 65B:588–597
2. Ahlbäck S, Bauer GCH, Bohne WH (1968) Spontaneous osteonecrosis of the knee. Arthritis Rheum 11:705–733
3. Bonutti PM, Thorsten SM, Delanois RE, McMahon M, McCarthy JC, Mont MA (2006) Osteonecrosis of the knee after laser or radiofrequency-assisted arthroscopy: treatment with minimally invasive knee arthroplasty. J Bone Joint Surg 88A:69–75
4. Cruess RL (1986) Osteonecrosis of the bone: current concepts as to etiology and pathogenesis. Clin Orthop Relat Res 208:30–39
5. Fukubayashi T, Kurosawa H (1980) The contact area and pressure distribution pattern of the knee. Acta Orthop Scand 51:871–879
6. Fukuda Y, Takai S, Yoshino N et al (2000) Impact load transmission of the knee joint–influence of leg alignment and the role of meniscus and articular cartilage. Clin Biomech 15:516–521
7. Gold GE, Busse RF, Beehler C, Han E, Brau AC, Beatty PJ, Beaulieu CF (2007) Isotropic MRI of the knee with 3D fast spin-echo extended echo-train acquisition (XETA): initial experience. Am J Roentgenol 188:1287–1293
8. Hirschmann MT, Adler T, Rasch H, Hügli RW, Friederich NF, Arnold MP (2010) Painful knee joint after ACL reconstruction using biodegradable interference screws-SPECT/CT a valuable diagnostic tool? A case report. Sports Med Arthrosc Rehabil Ther Technol 2:24

9. Hirschmann MT, Iranpour F, Davda K, Rasch H, Hugli R, Friederich NF (2010) Combined single-photon emission computerized tomography and conventional computerized tomography (SPECT/CT): clinical value for the knee surgeons? Knee Surg Sports Traumatol Arthrosc 18:341–345
10. Kuster MS, Wood GA, Stachowiak GW, Gächter A (1997) Joint load considerations in total knee replacement. J Bone Joint Surg 79B:109–113
11. Linsenmaier U, Kersting S, Schlichtenhorst K, Putz R, Pfeifer KJ, Reiser M, Müller-Gerbl M (2003) Functional CT imaging: load-dependent visualization of the subchondral mineralization by means of CT osteoabsorptiometry (CT-OAM). Rofo 175:663–669
12. Lotke PA, Ecker ML (1988) Osteonecrosis of the knee: current concepts review. J Bone Joint Surg 70A:470–473
13. MacDessy SJ, Brophy RH, Bullough PG, Windsor RE, Sculco TP (2008) Subchondral fracture following arthroscopic knee surgery. J Bone Joint Surg 90A:1007–1012
14. Mears SC, McCarthy EF, Jones LC, Hungerford DS, Mont MA (2009) Characterization and pathological characteristics of spontaneous osteonecrosis of the knee. Iowa Orthop J 29:38–42
15. Meyer S, Lobenhoffer P (2008) Knee and shoulder arthroscopy. Positioning and thermal injuries. Orthopade 37:1056, 1058–1060, 1062–1064
16. Neter J, Kutner MH, Nachtsheim CJ, Wasserman W (1996) Applied linear statistical models, 4th edn. Irwin, Chicago
17. Pape D, Lorbach O, Anagnostakos K, Kohn D (2008) Osteonecrosis in the postarthroscopic knee. Orthopade 37:1099–1100
18. Pape D, Seil R, Anagnostakos K, Kohn D (2007) Postarthroscopic osteonecrosis of the knee. Arthroscopy 23:428–438
19. Pruès-Latour V, Bonvin JC, Fritschy D (1998) Nine cases of osteonecrosis in elderly patients following arthroscopic meniscectomy. Knee Surg Sports Traumatol Arthrosc 6:142–147
20. Rohlmann A, Zilch H, Bergmann G, Kölbel R (1980) Material properties of femoral cancellous bone in axial loading. Arch Orthop Traumatol Surg 97:95–102
21. Tashiro Y, Miura H, Nakanishi Y, Okazaki K, Iwamoto Y (2009) Evaluation of skills in arthroscopic training based on trajectory and force data. Clin Orthop Relat Res 467:546–552
22. Taylor SJ, Walker PS (2001) Forces and moments telemetered from two distal femoral replacements during various activities. J Biomech 34:839–848
23. Taylor SJ, Walker PS, Perry JS, Cannon SR, Woledge R (1998) The forces in the distal femur and the knee during walking and other activities measured by telemetry. J Arthroplasty 13:428–437
24. Tuijthof GJM, van Sterkenburg MN, Sierevelt IN, van Oldenrijk J, Van Dijk CN, Kerkhoffs GMMJ (2010) First validation of the passport training environment for arthroscopic skills. Knee Surg Sports Traumatol Arthrosc 18:218–224
25. Yamamoto T, Bullough PG (2000) Spontaneous osteonecrosis of the knee: the result of subchondral insufficiency fracture. J Bone Joint Surg 82A:858–866