Collateral Ligament Laxity in Knees: What Is Normal?

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Abstract

Background Proper alignment and balancing of soft tissues of the knee are important goals for TKA. Despite standardized techniques, there is no consensus regarding the optimum amount of collateral ligament laxity one should leave at the end of the TKA.

Questions/purposes I asked (1) what is the collateral laxity in young healthy volunteers, and (2) is there a difference in collateral laxity between males and females.

Methods The femorotibial mechanical angle (FTMA) was measured in 314 knees in healthy volunteers aged 19 to 35 years. Subjects with a history of pain, malalignment, dysplasia, or trauma were excluded. Twenty-five knees were excluded because the hip center could not be acquired, and 22 were excluded because of a history of

pain and trauma, leaving 267 knees for inclusion in the study. Of these, 155 were from men and 112 were from women. A validated method using a computer navigation system was used to obtain the measurements. A 10-Nm torque was used to stress the knee in varus and valgus at 0° extension and 15° flexion. An independent t-test and ANOVA were applied to the data to calculate any significant difference between groups ($p < 0.05$).

Results The mean (SD) unstressed supine FTMA was varus of 1.2° (SD, 4°) in 0° extension and varus of 1.2° (SD, 4.4°) in 15° flexion ($p = 0.88$). On varus torque of 10 Nm, the supine FTMA changed by a mean of 3.1° (SD, 2°) (95% CI, 2.4°–3.8°; $p < 0.001$) in 0° extension and 6.9° (SD, 2.6°) (95% CI, 6.2°–7.7°; $p < 0.001$) in 15° flexion. On valgus torque of 10 Nm, the FTMA changed by a mean of 4.6° (SD, 2.2°) (95% CI, 3.9°–5.3°; $p < 0.001$) in 0° extension and 7.9° (SD, 3.4°) (95% CI, 7.1°–8.7°; $p < 0.001$) in 15° flexion. The mean unstressed FTMA in 0° extension was varus of 1.7° (SD, 4°) in men and 0.4° (SD, 3.9°) in women ($p = 0.01$). Differences in collateral ligament laxity were seen between men and women ($p < 0.001$ for valgus torque and 0.035 for varus torque in 15° flexion). With valgus torque at 0° flexion, the supine FTMA change was valgus of 4.2° (SD, 2.0°) for men and 5.0° (SD, 2.4°) for women, while at 15° flexion the FTMA change was valgus 7.6° (SD, 3.6°) for men and 8.3° (SD, 3.2°) for women. With varus torque at 0° flexion, additional varus was −3.0° (SD, 1.8°) for men and −3.3° (SD, 2.2°) for women, while at 15° flexion, varus was −7.0° SD, (2.5°) for men and −6.9° (SD, 2.8°) for women.

Conclusions The collateral laxity in young healthy volunteers was quantified in this study. The collateral ligament laxity is variable in different persons. In addition, ligaments in women are more lax than in men in valgus stress.

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Clinical Relevance This study was conducted on young, healthy knees. Whether the findings are applicable to arthritic knees and replaced knees needs additional evaluation. However the findings provide a baseline from which to work in the evaluation of arthritic knees and in the case of TKA.

Introduction

Traditionally, the goal of a TKA has been to create a neutral femorotibial mechanical angle (FTMA) with a balanced knee. Achievement of proper alignment and soft tissue balance in the coronal plane is important for long-term success of a TKA. Studies have shown that malalignment and imbalance can lead to failure of a TKA, particularly via polyethylene wear and loosening [2, 23, 26]. Computer-assisted navigation systems and patient-specific cutting blocks have been used to help orthopaedic surgeons achieve individual patient-specific neutral alignment in TKAs [1, 14, 18, 25]. Collateral soft tissue imbalance has been implicated as one of the factors affecting weightbearing alignment of the knee [31]. Anatomic variations in knee alignment exist between different races [12] and between males and females [5]. Alignment of normal limbs in the coronal plane measured with CT scanograms at the hip, knee, and ankle have shown that 98% of normal limbs do not have a neutral mechanical axis and 76% of normal limbs have a deviation greater than 3° from neutral [11]. Therefore, surgical correction of the arthritic knee to establish a straight mechanical axis does not represent a correction to normal alignment [4, 11, 15]. Additionally, it has been shown that nonweight-bearing alignment in the lying position is different from alignment in the weightbearing standing position [6, 31]. This applies to arthritic and replaced knees but more so in the former [31].

The results of knee arthroplasties are affected not only by alignment but also by soft tissue balance [2, 23, 26]. Instability after knee arthroplasty is one of the major causes for failure [26]. Computer navigation has been used to show the balancing in quantitative terms during surgery. To achieve a desired laxity is possible to some extent; however, an understanding of normal laxity is important to achieve the desired amount during surgery.

There is no consensus regarding normal collateral ligament laxity. In the United Kingdom, traditionally surgeons are taught to have approximately 2° collateral ligament laxity in either direction at the end of the procedure, although there is no specific scientific basis for choosing this figure for every TKA. The literature regarding normal knee collateral ligament laxity in living tissues is minimal [32]. An understanding of normal knee alignment and mediolateral laxity in the knee specific to individual

patients may be necessary to further improve outcomes after TKA. Recently, computer navigation was used on an outpatient basis to evaluate knee alignment of patients with arthritis [8].

I wished to determine (1) how much collateral knee laxity was present in young healthy volunteers, and (2) if there is a difference in collateral laxity between males and females?

Subjects and Methods

In this multicenter study, the FTMA was measured in the knees of healthy volunteers between 19 and 35 years old at six centers in India. The FTMA was defined as the angle formed by the femoral and tibial mechanical axes in the coronal plane. Persons with any history of pain in the knee or leg, alignment problems in the legs, developmental dysplasia, previous trauma, or familial history of developmental or alignment problems were excluded from the study. A total of 314 knees were tested. Twenty-five knees were excluded because the hip center could not be acquired, and 22 were excluded owing to a history of pain and trauma. The hip center acquisition may fail sometimes which requires the hip to be rotated in a circular motion to be able to calculate its center kinematically. The reason for failure to register is that awake subjects (as they were in this study) may find it difficult to relax their muscles enough for the center to be registered. Therefore, during registration, instead of just the hip moving, the pelvis also may move, in which case the computer will reject a wrong center of the hip. After exclusions, 267 knees were included. Of these, 155 were from men and 112 from women; there were 134 right knees and 133 left. In total, 132 persons had bilateral evaluation of their knees and three had only one knee assessed (two right and one left knee). The mean age of the patients was 26.2 years (SD, 4.4 years). For males it was 26.1 (SD, 4.1) and for females it was 26.4 years (SD, 4.9) ($p = 0.634$).

A power calculation was performed before starting the study with respect to comparison of male and female subjects. The calculation was based on data from a previous study using the same method of measurement [8]. To detect a difference of 1° with a 2.5° SD, an alpha of 0.05, and power of 80%, it was calculated that a minimum of 100 knees was needed in each group.

A validated method of measurement using a computerized infrared-based navigation system (OrthoPilot®; B Braun Melsungen AG, Tutlingen, Germany) was used for measurement of the FTMA [8]. The measurements were taken by one surgeon (KD) who has experience using computer navigation and performing knee arthroplasties. Demographic data were recorded and informed consent

Fig. 1 The trackers and straps used in the current study are shown. One tracker was attached to the thigh and another to the leg using the fiberoptic straps.

was obtained from each volunteer. One tracker was attached to the thigh and another to the leg using fiberoptic straps (Fig. 1). The trackers are tracked in all six degrees of freedom by the computer.

The computer software used the transepicondylar plane to define knee orientation.

The centers of the head of the femur, knee, and ankle were registered. The computer produced a mechanical axis by joining these centers. The centers of the hip and knee were calculated kinematically, as they are acquired during knee arthroplasty using computer navigation. The ankle center was registered anatomically with the most prominent medial and lateral malleoli, as in TKAs, using computer navigation. Any movement of the knee can be seen as a three-dimensional movement of three planes in relation to each other which are tracked in real time by the trackers attached to the thigh and knee. The flexion and varus-valgus angles are denoted by the sagittal and coronal planes, respectively. The rotational plane was calculated by the software based on the transepicondylar plane. The system is accurate up to 1° [8]. A mark was made over the skin 25-cm distal to the joint line. This point was used to apply a measured varus and valgus force of 40 N with a digital loading device with a nonelastic strap, thus making a torque of 10 Nm at the joint level. The FTMA was measured with the subject in the supine position without any force applied in 0° extension and 15° flexion. The FTMA also was measured with 10-Nm torque in the valgus and varus directions in 0° extension and 15° flexion. The FTMA in the coronal and sagittal planes can be seen clearly on the computer screen (Fig. 2). As weightbearing will produce its own forces/moments, a measured 10 Nm torque would be impossible to apply while weightbearing. Therefore, nonweightbearing application of the torque was chosen for this study.

Fig. 2 Alignment in the coronal and sagittal planes is seen on the computer screen.

Statistical analyses were performed using SPSS® software (Version 19; IBM Corp, Armonk, NY, USA). Results are presented as mean and SD. The differences between the mean unstressed supine FTMA in 0° and 15° flexion were compared using a paired t-test. Differences in mean supine FTMA across the three applied torque conditions at 0° and 15° flexion were compared using ANOVA. Where differences were found, least significant difference post hoc tests were performed to identify differences between conditions. The difference in mean unstressed supine FTMA between sexes was assessed using an independent t-test. For all analyses a p value of 0.05 was considered significant.

Results

The mean unstressed supine FTMA was varus of 1.2° (4°) in 0° extension and 1.2° (4.4°) in 15° flexion ($p = 0.88$). There was a difference in lower limb alignment across the three different stress conditions at 0° ($p < 0.001$) and 15° ($p < 0.001$) flexion. At 0° flexion with an applied varus torque of 10 Nm, the mean supine FTMA was 3.1° (95% CI, 2.4°–3.8°; $p < 0.001$) more varus and with an applied valgus torque of 10 Nm, the mean supine FTMA was 4.6° (95% CI, 3.9°–5.3°; $p < 0.001$) more valgus. In 15° flexion with varus torque, the mean FTMA was 6.9° (95% CI, 6.2°–7.7°; $p < 0.001$) more varus and with valgus torque, the mean FTMA was 7.9° (95% CI, 7.1°–8.7°; $p < 0.001$) more valgus.

The mean unstressed FTMA in 0° extension was varus of 1.7° (4°) in men and 0.4° (3.9°) in women (mean difference, 1.3°; 95% CI, 0.3°–2.2°; $p = 0.010$). Women showed more collateral ligament laxity in valgus than men when 10-Nm torque was applied (Table 1) ($p < 0.001$ for valgus torque in 0° flexion and 15° flexion). However on

varus torque a difference was seen only at 15° flexion ($p = 0.035$) but not at 0° flexion ($p = 0.90$) (Table 1).

Discussion

Proper alignment and balancing of soft tissues of the knee are important goals for TKA. Despite standardized techniques, there is no consensus regarding the optimum amount of collateral ligament laxity one should leave at the end of a TKA. The objectives of this study were to evaluate normal collateral ligament laxity on varus and valgus stress testing in 0° extension and 15° flexion and to compare gender differences in collateral ligament laxity. The results of the study indicate wide variation in FTMA and collateral ligament laxity even among individuals with functionally normal knees. To the best of my knowledge, this is the largest study quantifying collateral ligament laxity on normal human knees.

There are limitations to this study. The values obtained are from subjects in one country (India) and may not be applicable to a global population. The study was based on extracutaneous attachment of trackers, which theoretically may not be as accurate as bony attachment, although these have been validated in studies using the same method and extracutaneous attachment [8, 9, 24]. Inter- and intraregistration measurements using the same straps have been validated using this method, which uses a specialized fibroelastic strap attachment as used in the current study [8]. Another limitation is percutaneous palpation of the medial and lateral epicondyles, which can be subject to variation. This should not make any substantial difference to the measurements in extension, as the sagittal and coronal planes are 90° to each other and to the rotational plane. Thus any rotational plane registration error of epicondyle palpation should not have much of an effect in 0° flexion but can have some effect in more flexion. Previous experience with this method has shown that this effect can be seen in measurements at greater than 40° flexion, but the FTMA measurements are accurate up to 40° flexion [24]. In the current study, measurements were taken only to 15° flexion. The changing underlying muscle mass with flexion also could affect the measurements when the knee moves into flexion, although the flexion measurements were only to 15° flexion. Another study used similar methods for standardizing measurement of coronal laxity measurements [9]. In that study three clinicians performed six examinations each and found the FTMA to be repeatable with a SD of 1.1° for each clinician with similar means for each clinician [9]. The application of varus and valgus torque, although standardized to 10 Nm, may not have been exactly 10 Nm. This may have differed slightly at the end application point, as it was applied in a gross valgus-varus

direction. In addition, the torque was not applied at one point in an exact plane. In practice, it is not possible to have absolute control of force application with uncontrollable load and boundary conditions on conscious human beings. This may lead to an error of as much as 1 Nm. In this study, the last 1 Nm torque likely did not have much effect on the FTMA measurement because the ligaments already were stretched out of their laxity when the initial torque was applied. In normal practice, when collateral ligament laxity and balance are assessed in the clinic or during surgery, it is in the gross varus and valgus directions only, with a subjective force applied by the surgeon, which can vary among surgeons.

The results of the current study indicate that the majority of normal individuals do not have a neutral mechanical axis (mean, 1.2° varus; SD, 4°). This is consistent with a previous study which found a mean varus of 1.33° (SD, 2.34°) to the mechanical axis [4]. Parratte et al. [22] found no difference in 15 year-revision rates for knees aligned within 3° of neutral. Knowledge of normal individual FTMA and collateral ligament laxity can help the surgeon achieve better balancing after TKA. The current method can be a useful screening tool on an outpatient basis, especially if the contralateral knee of the patient is normal. Creaby et al. [10] found no difference in varus-valgus laxity between varus arthritic knees and a control group of normal knees. Markolf et al. [19] found the mean varus-valgus laxity to be 6.7° in full extension. Knowledge of the normal collateral ligament laxity of the knee is essential to determine how tight the prosthetic knee should be balanced. Heesterbeek et al. [13] used a radiographic method and Telos tensioner (Fa Telos, Medizintechnik GmbH, Griesheim, Germany) with 15-Nm torque and reported a mean varus laxity of 2.8° (SD, 1.3°) and valgus laxity of 2.3° (SD, 0.8°) in full extension in normal patients. Yoo et al. [32] reported 6.7° to 7.2° varus laxity and 3.9° to 4.3° valgus laxity in 20° knee flexion in normal Korean patients using a custom-made measurement scale. The results of the current study are consistent with the above-mentioned studies. At 0° flexion with an applied varus torque of 10 Nm, the mean supine FTMA was 3.1° (95% CI, 2.4°–3.8°; $p < 0.001$) more varus and with an applied valgus torque of 10 Nm the mean supine FTMA was 4.6° (95% CI, 3.9°–5.3°; $p < 0.001$) more valgus, thus a total 7.7° varus valgus laxity in extension. In 15° flexion with varus torque the mean supine FTMA was 6.9° (95% CI, 6.2°–7.7°; $p < 0.001$) more varus and with valgus torque, the mean supine FTMA was 7.9° (95% CI, 7.1°–8.7°; $p < 0.001$) more valgus, thus a total varus-valgus laxity of 14.8°. This increased laxity in 15° flexion could be the effect of tissues, such as the posterior capsule, which are tight in extension but lax in flexion, and therefore the effect is negated in flexion measurements, allowing more collateral ligament laxity.

Table 1. Femorotibial mechanical angle changes from no stress to application of stress*

Stress	Femorotibial mechanical angle (°)		p value
	Male	Female	
Varus 0° extension	−3.0 (1.8)	−3.3 (2.2)	0.090
Varus 15° flexion	−7.0 (2.5)	−6.9 (2.8)	0.035
Valgus 0° extension	4.2 (2.0)	5.0 (2.4)	< 0.001
Valgus 15° flexion	7.6 (3.6)	8.3 (3.2)	0.001

* Varus or valgus collateral torque of 10 Nm; values expressed as mean and SD; negative values indicate varus.

The alignment difference between male and female leg alignment is well known [4, 21]. Women have slightly more valgus compared with men. Bellemans et al. [4] found FTMA to be a varus of 1.9° (SD, 2.1°) in men compared with 0.8° (SD, 2.4°) in women. In my study, similar values Oof FTMA were found, with a varus of 1.7° (SD, 4°) in men and 0.4° (SD, 3.9°) in women (mean difference, 1.3°; 95% CI, 0.3°–2.2°; $p = 0.010$). In a study done on arthritic knees, van der Esch et al. [30] found women had more varus-valgus laxity (7.7° [SD, 2.9°]) compared with men (4.6° [SD, 2.2°]) ($p < 0.001$). There was a difference seen in collateral laxity between men and women in the current study as well (Table 1). This was more significant with valgus torque in 0° and 15° flexion. It also was seen with varus torque when the posterior structures were relaxed (15° flexion) but not in 0° extension. This may indicate the posterior or other supporting ligaments/structures play equally important roles in men and women preventing varus stress in extension. It also may mean that the stiffness comes into play in resisting varus torque in extension earlier than in other directions. It is known that the female ligaments are more lax than male ligaments [27, 28], and possibly related to the hormone milieu of the female gender [27, 28]. Shultz et al. [27] reported anterior laxity was greater in women than in men. In women, anterior laxity also varied depending on the day of the menstrual cycle [27]. They found estrogens and progesterones increased laxity. In our study, a laxity difference was found between men and women but the study was not designed to note the day of the cycle to refine the results even further. The difference in male and female ligamentous laxity is well recognized [27]. The current study quantitatively evaluated this difference in collateral laxity.

The question with TKA is what amount of laxity is needed to achieve a good result. Previous studies have reported that 3° to 4° varus and valgus laxity is compatible with good results in PCL-retaining TKAs [16, 18, 20]. However, given the wide range of valgus and varus laxity, it may be useful to measure the healthier knee in patients with unilateral knee osteoarthritis and reproduce the same at the time of surgery. One of the challenges during surgery is to assess the laxity and axis accurately. Traditionally tensors,

spacers, and subjective feel have been used. Computer navigation using infrared tracking has been used intraoperatively to provide surgeons with quantitative measurement tools that permit real-time assessment of lower-limb kinematics [3, 7, 29]. The intraoperative use of a computer navigation system may enable the surgeon to reproduce the FTMA and varus-valgus laxities more accurately, as one will have numbers to work with that can be seen in real time during surgery. However, this potential benefit must be considered speculative, as the research regarding how much collateral ligament laxity is needed to satisfy patients' needs in terms of pain or function is fairly preliminary [16, 17]. It is possible that they may benefit from greater or less laxity than the normal, healthy human knee, which is what was studied here. Future studies should evaluate this.

I found the mean mechanical axis of the knee in normal individuals to be in varus. The collateral ligament laxity was variable among individuals and ligaments were more lax in women than men in valgus torque. Preoperative assessment of laxity may help surgeons during surgery, but additional studies must evaluate whether the same, lesser, or more laxity would benefit replaced knees.

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References

1. Bankes MJ, Back DL, Cannon SR, Briggs TW. The effect of component malalignment on the clinical and the radiological outcome of the Kinemax total knee replacement. *Knee*. 2003;10:55–60.
2. Bargren JH, Blaha JD, Freeman MA. Alignment in total knee arthroplasty: correlated biomechanical and clinical observations. *Clin Orthop Relat Res*. 1983;173:178–183.
3. Bathis H, Perlick L, Tingart M, Luring C, Zurakowski D, Grifka J. Alignment in total knee arthroplasty: comparison of computer-assisted surgery with the conventional technique. *J Bone Joint Surg Br*. 2004;86:682–687.
4. Bellemans J, Colyn W, Vandenuecker H, Victor J. The Chitranjan Ranawat Award: Is neutral mechanical alignment normal for all patients? The concept of constitutional varus. *Clin Orthop Relat Res*. 2012;470:45–53.
5. Bourne RB, Chesworth BM, Davis AM, Mahomed NN, Charron KD. Patient satisfaction after total knee arthroplasty: who is satisfied and who is not? *Clin Orthop Relat Res*. 2010;468:57–63.
6. Brouwer RW, Jakma TS, Bierma-Zeinstra SM, Ginai AZ, Verhaar JA. The whole leg radiograph: standing versus supine for determining axial alignment. *Acta Orthop Scand*. 2003;74:565–568.

7. Chauhan SK, Scott RG, Breidahl W, Beaver RJ. Computer-assisted knee arthroplasty versus a conventional jig-based technique: a randomised, prospective trial. *J Bone Joint Surg Br.* 2004;86:372–377.
8. Clarke JV, Riches PE, Picard F, Deakin AH. Non-invasive computer-assisted measurement of knee alignment. *Comput Aided Surg.* 2012;17:29–39.
9. Clarke JV, Wilson WT, Wearing SC, Picard F, Riches PE, Deakin AH. Standardising the clinical assessment of coronal knee laxity. *Proc Inst Mech Eng H.* 2012;226:699–708.
10. Creaby MW, Wrigley TV, Lim BW, Bowles KA, Metcalf BR, Hinman RS, Bennell KL. Varus-valgus laxity and passive stiffness in medial knee osteoarthritis. *Arthritis Care Res (Hoboken).* 2010; 62:1237–1243.
11. Eckhoff DG, Bach JM, Spitzer VM, Reinig KD, Bagur MM, Baldini TH, Flannery NM. Three-dimensional mechanics, kinematics, and morphology of the knee viewed in virtual reality. *J Bone Joint Surg Am.* 2005;87(suppl 2):71–80.
12. Harvey WF, Niu J, Zhang Y, McCree PI, Felson DT, Nevitt M, Xu L, Aliabadi P, Hunter DJ. Knee alignment differences between Chinese and Caucasian subjects without osteoarthritis. *Ann Rheum Dis.* 2008; 67:1524–1528.
13. Heesterbeek PJ, Verdonchot N, Wymenga AB. In vivo knee laxity in flexion and extension: a radiographic study in 30 older healthy subjects. *Knee.* 2008;15:45–49.
14. Hovinga KR, Lerner AL. Anatomic variations between Japanese and Caucasian populations in the healthy young adult knee joint. *J Orthop Res.* 2009;27:1191–1196.
15. Howell SM, Kuznik K, Hull ML, Siston RA. Longitudinal shapes of the tibia and femur are unrelated and variable. *Clin Orthop Relat Res.* 2010;468:1142–1148.
16. Ishii Y, Matsuda Y, Ishii R, Sakata S, Omori G. Coronal laxity in extension in vivo after total knee arthroplasty. *J Orthop Sci.* 2003;8:538–542.
17. Ishii Y, Noguchi H, Matsuda Y, Takeda M, Walker SA, Komistek RD. Effect of knee laxity on in vivo kinematics of meniscal-bearing knee prostheses. *Knee.* 2007;14:269–274.
18. Jenny JY, Boeri C. Unicompartmental knee prosthesis: implantation with a non-image-based navigation system. In: DiGioia A, Jaramaz B, Picard F, Nolte LP, eds. *Computer and Robotic Assisted Knee and Hip Surgery.* New York, NY: Oxford University Press Inc; 2004:181–188.
19. Markolf KL, Graff-Radford A, Amstutz HC. In vivo stability: a quantitative assessment using an instrumented clinical testing apparatus. *J Bone Joint Surg Am.* 1978;60:664–674.
20. Matsuda Y, Ishii Y, Noguchi H, Ishii R. Effect of flexion angle on coronal laxity in patients with mobile-bearing total knee arthroplasty prostheses. *J Orthop Sci.* 2005;10:37–41.
21. Nguyen AD, Shultz SJ. Sex differences in clinical measures of lower extremity alignment. *J Orthop Sports Phys Ther.* 2007; 37:389–398.
22. Parratte S, Pagnano MW, Trousdale RT, Berry DJ. Effect of mechanical axis alignment on the fifteen-year survival of modern, cemented total knee replacements. *J Bone Joint Surg Am.* 2010;92:2143–2149.
23. Ritter MA, Faris PM, Keating EM, Meding JB. Postoperative alignment of total knee replacement: its effect on survival. *Clin Orthop Relat Res.* 1994;299:153–156.
24. Russell DF, Deakin AH, Fogg QA, Picard F. Non-invasive, non-radiological quantification of anteroposterior knee joint ligamentous laxity: a study in cadavers. *Bone Joint Res.* 2013;2: 233–237.
25. Saragaglia D, Picard F, Chaussard C, Montbarbon E, Leitner F, Cinquin P. [Computer-assisted knee arthroplasty: comparison with a conventional procedure. Results of 50 cases in a prospective randomized study] [in French]. *Rev Chir Orthop Reparatrice Appar Mot.* 2001;87:18–28.
26. Sharkey PF, Hozack WJ, Rothman RH, Shastri S, Jacoby SM. Insall Award paper: Why are total knee arthroplasties failing today? *Clin Orthop Relat Res.* 2002;404:7–13.
27. Shultz SJ, Sander TC, Kirk SC, Perrin DH. Sex differences in knee joint laxity change across the female menstrual cycle. *J Sports Med Phys Fitness.* 2005;45: 594–603.
28. Shultz SJ, Schmitz RJ, Beynon BD. Variation in varus/valgus and internal/external rotational knee laxity and stiffness across the menstrual cycle. *J Orthop Res.* 2011;29:318–325.
29. Stulberg DS, Loan P, Sarin V. Computer-assisted navigation in total knee replacement: results of an initial experience in thirty-five patients. *J Bone Joint Surg Am.* 2002;84(suppl 2):90–98.
30. van der Esch M, Steultjens MPM, Lems WF, Dekker J. Gender difference in varus–valgus laxity in osteoarthritis of the knee. *Scand J Rheumatol.* 2007;36:157–159.
31. Willcox NM, Clarke JV, Smith BR, Deakin AH, Deep K. A comparison of radiological and computer navigation measurements of lower limb coronal alignment before and after total knee replacement. *J Bone Joint Surg Br.* 2012;94:1234–1240.
32. Yoo JC, Ahn JH, Sung KS, Wang JH, Lee SH, Bae SW, Ahn YJ. Measurement and comparison of the difference in normal medial and lateral knee joint opening. *Knee Surg Sports Traumatol Arthrosc.* 2006;14:1238–1244.