Swelling assessment after total knee arthroplasty

LI Ka Yau¹, FU Henry², CHEUNG Man Hong², CHEUNG Amy³, CHAN Wai Kwan Vincent³, CHAN Ping Keung² and CHIU Kwong Yuen²

Abstract

Background: Total knee arthroplasty is a commonly performed elective orthopaedic surgery. Patients may endure substantial knee swelling following surgery, which are attributable to both effusion and edema. Studies have been aiming to identify an accurate and reliable method to quantify post-operative knee swelling to aid monitoring progress and treatment. The aim of this article was to review the means of clinically applicable measurements for knee swelling post TKA.

Methods: The medical literature was searched using PubMed to search for articles published using the terms knee edema, effusion, swelling, knee arthroplasty, knee replacement, total knee arthroplasty, total knee replacement, TKA, TKR. Year of publication was not restricted. Only English language publications were included. Only full-text published articles from peer-reviewed journals were eligible for inclusion. The knee swelling measurement methods used in post TKA were reviewed.

Results: Advancement in bioimpedance spectroscopy and handheld 3D scanning technology allows quick and precise quantification of knee swelling volume that the traditional clinical circumferential measurement and volumetric measurement lack. Handheld 3D scanning is also a potential tool to estimate the change of knee effusion volume and muscular volume after the surgery. Magnetic resonance imaging is accurate in effusion measurement but also the most time and resource demanding method.

Conclusion: Bioimpedance spectroscopy and 3D scanning technology can be the future tools for clinically measurement of knee swelling after total knee arthroplasty.

Keywords
knee swelling, knee effusion, total knee arthroplasty, post-operative monitoring, knee girth, bioimpedance spectroscopy, 3D scanning, diagnostic ultrasound, magnetic resonance imaging

Introduction

Background

Knee osteoarthritis (OA) is a prevalent and debilitating degenerative joint condition, with 80% of OA patients experiencing movement restrictions and 25% of them suffering from limitations in daily activities.¹ To alleviate pain and restore the quality of life in patients with severe OA knee, knee arthroplasty has been frequently performed all around the world.²,³ An international survey found out that

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the incidence of total knee replacement were 175 procedures/100,000 population with the highest of 234 procedures/100,000 population for the United States.4 Although total knee arthroplasty is recognized as a highly successful therapeutic procedure for knee osteoarthritis, significant joint swelling is frequent following the surgery as figure reporting prevalence of 15.6% among patients after TKA.5,6 Anatomically, swelling can occur within the joint or outside the joint capsule. Swelling caused by intra-articular fluid accumulation inside a joint is called effusion.8 Effusion after TKA due to surgical insults progresses from hemorrhosis to serosanguineous followed by serous with time. Swelling outside the joint capsule mostly originate from edema of surrounding soft tissues, these include bursa, muscles, subcutaneous fat and skin.9 Swelling after TKA results in pain, inflammation, reduced range of motion, inhibition of quadriceps, functional limitation and negative perception of recovery.10,11 This review compares various clinically applicable means of swelling assessment after TKA.

**Method**

The medical literature was searched using PubMed to search for articles published using the terms knee edema, effusion, swelling, knee arthroplasty, knee replacement, total knee arthroplasty, total knee replacement, TKA, TKR. Year of study publication was not restricted. Only English language publications were included. Full-text published articles and abstracts from peer-reviewed journals only were eligible for inclusion. The knee swelling measurement methods used in non-clinical and TKA clinical trials were reviewed.

**Review of Swelling Assessment after Total Knee Arthroplasty**

**Circumferential measurement.** Girth measurements are routinely performed clinically to evaluate muscle atrophy or joint swelling following injury and surgery.12 For knee girth measurement, subjects are positioned supine with their knees in an extended position and lower extremity musculature relaxed. A targeted location of the girth measurement is marked before circumferential measurement with a nonelastic tape. It was reported that knee girth 1 cm above the patella correlates better with aspirated synovial fluid volume than girth at the mid-patella level. It was also estimated that a one-cm reduction in circumference was equivalent to around 40 mL of fluid aspiration.13 A psychometric study has shown excellent intra-tester reliability (Intraclass Correlation Coefficient, ICC = 0.99) and inter-tester reliability (ICC = 0.98–0.99) in subjects undergoing TKA.14 Despite the correlation and high reliability, Guex and Perrin (2000)15 argued that a single circumferential measurement could not be extrapolated to give the measurement of volume.

A multiple girth measurement method was proposed by Sitzia (1995)16 and a frustum formula (Figure 1) was postulated for imprecise estimation of limb volume by measuring a proximal and distal girth and the distance between the points of girth measurement. It was demonstrated that the frustum formula for lower limb volume estimation displayed an insignificant difference and excellent correlation with the volume determined by water displacement (r = 0.86–0.87), as well as excellent intra-tester reliability (ICC = 0.90–0.99) and good inter-tester reliability (ICC = 0.85–0.88).17 An excellent intra-tester reliability (ICC = 0.99) and inter-tester reliability (ICC = 0.97–0.99) were also reported by using a frustum formula for knee volume estimation by measuring the girth at popliteal fossa, 5 cm and below popliteal fossa.18 However, the major limitation of girth measurement is that it does not distinguish between edema volume and muscular volume and, in the case of post-TKA where muscular atrophy and knee effusion could be substantial, this limitation is a threat to precise knee effusion measurement. Despite the limitation, circumferential measurement is still often adopted as a quick clinical tool for imprecise estimation of knee swelling measurement after TKA.

**Volumetric measurement**

Water displacement is traditionally the gold standard of volume assessment of limbs.19 A tall water tank was filled until overflow and the concerned lower limb is immersed to displace the water into another overflow tank which measures the limb volume. Another way of performing water displacement for knee volumetry is by first instructing a subject to immerse the limb into the empty acrylic box while remaining as motionless as possible. The assessor will then pour water into the box until the water level reaches a lower reference point, such as 5 cm below the fold of the popliteal fossa or superior border of the tibial tuberosity. A second water container with the exact volume of water needed to fill the empty box up to the upper reference point, such as 5 cm above the fold of the popliteal fossa or 1 cm above the superior border of the patella, is poured into the acrylic box. The remaining water in the container is the same volume as the knee. It was reported that the intra-tester reliability ICC and inter-tester reliability ICC were 0.82 and 0.69–0.83 respectively.18 Despite being the gold standard of limb volumetry, there are several drawbacks to this method. Filling the water tank, carefully situating the subject’s leg, waiting for the water level to stabilize, and changing the water between subjects to avoid cross-infection are all time-consuming procedures.20 Subjects with open wounds or skin diseases should avoid water displacement. Moreover, it does not
differentiate knee effusion volume and muscular volume of the measured lower limb.

**Bioimpedance spectroscopy**

Electrical bioimpedance is an estimation of body composition by measuring living tissues’ opposition to an alternating current (impedance). As the opposition to a current flow becomes lowered when fluid volume increases, any swelling in a limb can be reflected by a decrease in impedance measured.

By Ohm’s law, assuming a bioelectrical cylinder model of a fixed length (L), the opposition to AC flow (impedance, Z) is proportional to the potential difference (PD) across the cylinder and inversely proportional to the current measured (I).

\[
Z = \frac{PD}{I}
\]

Although a limb segment is not a uniform cylinder with constant conductivity, an empirical relationship can be established that the impedance of such a cylindrical structure is dependent on the specific impedance of the tissue (z), the volume of the cylinder (v), and the cylinder length (L) as shown in the equation below. Thus, the value of Z measured between two fixed points is proportional to the specific impedance of the tissue and inversely proportional to the tissue volume.

\[
Z = \frac{\pi h}{3} \left( r_1^2 + r_1 r_2 + r_2^2 \right)
\]

Figure 1. Frustum formula proposed by Sitzia (1995)

Theoretically, the capacitive effect of the cell membrane is high when the administered current is at zero frequency, producing high reactance and insulating the flow of current. Therefore, the current travels only through the extracellular compartment and the impedance measured (the R0 variable) reflects the volume of limb extracellular fluid. On the other hand, the low capacitive effect of the cell membrane when the current at infinite frequency allows current to pass through both the intracellular and extracellular compartments and the impedance measured (the Ri variable) reflects the total fluid volume. As post-surgical swelling is confined to the extracellular space, R0 could thus be considered as a potential indirect estimator of post-surgical swelling without the need to compensate for the metallic implant interference with measurement. During a bioimpedance spectroscopy (BIS) measurement, the R values are predicted using a Cole–Cole plot without the need of administering current at zero frequency or extremely high frequency. For a more detailed explanation of the principles, the reader is referred to the review by Kyle et al. (2004). A four-wire measurement method (Figure 2) can be used for knee swelling measurement: electrodes placed on the most distal girth measurement level of the leg, the most proximal girth measurement level of the thigh on each side and at 12 cm above the most distal leg electrode.

As for the evidence of BIS, it was demonstrated that BIS measurement for ankle swelling in subjects with ankle fracture correlated with volume measured by water displacement (r = −0.92, p = 0.001) better than single circumferential measurement (r = 0.81, p < 0.01). In the context of TKA, Pichonnaz et al. (2015) reported a good correlation between BIS R0 with lower limb volume calculated by frustum model (r = 0.73) and BIS intra- and inter-evaluator ICCs ranging from 0.89 to 0.99. Yet, the correlation of bioimpedance to knee effusion and muscle volume has not been investigated. Despite the uncertainties, bioimpedance spectroscopy has the potential to overcome the drawbacks of girth measurements as discussed above, offering an alternative measurement method that is applicable and non-invasive.

**Diagnostic ultrasound**

Doppler ultrasound examination can be performed on the knee to estimate the amount of knee effusion. According to the Outcome Measures in Rheumatology, the synovial fluid collection was defined as an anechoic or hypoechoic region that is displaceable and does not exhibit Doppler signal. Three major suprapatellar pouch recesses, including the midline suprapatellar, medial parapatellar, and lateral parapatellar, can all be evaluated. Mandl et al. (2012) showed that the suprapatellar scan of the knee in 30° flexion was the most sensitive position for detecting synovial fluid in knee...
joints. Measurements of knee effusion can be obtained from the medial, midline, and lateral sides of the anterior aspect of the suprapatellar region of the knees with the probe longitudinally placed. The maximal anteroposterior width of the effusion could be recorded, and the highest of the three suprapatellar measurements (medial, mid, and lateral) can be used for further analysis such as grading the amount of knee effusion (Figure 3). However, determining the true volume of effusion and differentiating it from extra-articular haematoma are very difficult because of the number of synovial recesses and the complex anatomy of the knee joint. Boldt et al. (2004) postulated the two-dimensional ellipsoid formula for a rough estimation of effusion volume, \( \frac{\pi \times a \times b}{4} \), where \( a \) and \( b \) are the largest transverse and anteroposterior diameters of the effusion in the suprapatellar pouch and medial and lateral gutters. Another limitation of ultrasound measurement is that the accuracy of detection can be influenced by factors such as the amount of effusion and clinicians’ experience. Despite being a semi-quantitative and operator-dependent method, the simplicity and accessibility of diagnostic ultrasound still make it a convenient tool for detecting knee effusion after TKA.

**Optometric measurement**

In 1997, an optoelectronic imaging device called Perometer (Perometer 350S, Pero-System, Wuppertal, Germany) was validated as a limb volumeter. It consists of a square frame embedded with multiple infrared light-emitting diodes and sensors and a stationary rail track where the frame can move along the long axis of the measuring extremity. Each emitting diode emits a frequency-modulated beam of infrared light and this modulated signal is sensed by three corresponding detecting sensors to determine the distance between the light source and the surface of the object being scanned by tri-angulation. The vertical and horizontal diameter of the measured limb can be used to calculate the limb volume with a circular or elliptical model. To assess knee volume, the subject will sit in an adjustable chair, with the leg to be measured centred within the measuring frame and the foot resting on the footrest. The square measuring frame is moved along the two reference points which can be 1 cm above the superior border of the patella and the superior border of the tibial tuberosity. Perometer offers quick measurement of limb volume, circumference, contour, and cross-sectional area and is safe to use on patients with open wounds or skin disorders. It was reported that there was a high correlation of measured knee volume in healthy individuals when comparing Perometer and water displacement \( r = 0.94, p < 0.01 \) but with a low degree of agreement (Limits of agreement (LOA) from \(-130\) to \(-207\) mL). No studies have investigated the use of Perometer in measuring knee volume in TKA. As for the limitation, similar to the limitation discussed above for the circumferential measurement method, Perometer does not distinguish between oedema volume and muscular volume.

In the last decade, the use of handheld optometric devices, such as handheld 3D scanners, has emerged in the fields of complex maxillofacial surgeries to capture complex anatomical morphology. A handheld 3D scanner composed of light-emitting diodes, light sensors and a motion-tracking device, either a manual articulating measuring arm or a stereo-photogrammetric system. Recent handheld 3D scanners mainly make use of a narrow band of laser or structured white or blue light to obtain imaging scans to reconstruct a 3D digital model of the scanner object. The light pattern projected can be in the form of grids, dots or stripes onto the surface of the object. The structured white or blue light can be safely viewed with the naked eye. On the other hand, laser triangulation is very robust against ambient light, shiny and dark object surfaces and eye protection may be required during laser scanning. During scanning, the light pattern is projected and laid onto the object, modifying its width and phase and the reflected light is being retrieved by the light sensor. The light sensors determine the distance between the light source and the surface of the object being
scanned by tri-angulation. The motion tracking device determines the position and orientation of the laser sensor or the object in 3D space. After scanning, the device software processes the raw data from light sensors and motion tracking devices to calculate the 3D coordinates from the returned patterns and produce an instantaneous 3D image of the capturing object (Figure 4(b)).

Recently, a study has attempted to utilize 3D surface scanning to monitor changes in knee surface morphology after anterior cruciate ligament reconstruction surgery.32 Telfer et al. (2020)32 used a portable 3D surface scanner (Sense; 3D Systems, Rock Hill, SC) to obtain a 360° scans of both the operated and the contralateral knee, extending at least 150 mm above the patella. The patella, the vastus lateralis muscle, and the vastus medialis muscle were identified as the area of interest, where serial scanning of these areas was performed to estimate the change in knee effusion volume and the atrophied volume of vastus lateralis muscle and the vastus medialis muscle after the surgery. The main limitation of this indirect estimation is that the accuracy of such data captured representing the actual muscle and swelling volumes is unknown. Nevertheless, the scan is fast and poses no risk to patients in terms of ionizing radiation or exclusions for those with metallic implants, as well as not requiring no specialist expertise to operate.31,33 Therefore, it is still a promising and clinically accessible technique for indirect knee volume measurement.

Magnetic resonance imaging

Magnetic resonance imaging (MRI) for knee swelling measurement (Figure 5) is not commonly performed in patients with TKA.34 A major technical obstacle for the evaluation of patient using MRI is the image artifacts because of metallic implants.35 In the research field, metallic artifact optimizing MRI sequences, 3-D volume rendering programs and MRI-compatible implant materials were developed and they can allow an more accurate estimation of knee effusion volume post-TKA.35,36 MRI using Slice-Encoding for Metal Artifact Correction (SEMAC) has been investigated in the setting of TKA.37 SEMAC corrects metal artifacts by adding z-phase encoding steps in the slice direction to corrects through-plane distortions.38 SEMAC is utilized in combination of another advanced MRI imaging strategy called View Angle Tilting (VAT) which provide in-plane distortion corrections.38 To quantify knee effusion volume, the voxels of the joint effusion sites on the images in the T2 sequence are selected using a voxel selection tool. By multiplying the number of selected voxels by the image voxel size, joint effusion volumes can be computed and calculated.

Excellent results had been achieved using MRI for knee effusion measurement. MRI using axial T2 weighted turbo spin echo (T2WTSE) and sagittal SPACE (Sampling Perfection with application optimized contrast using different angle evolutions) were reported to be highly correlated with the known volumes of saline injection into cadavers (r = 0.993 and 0.996, p < 0.001).39 It was also reported that in patients with knee osteoarthritis, an automated system for knee joint effusion volume measurement using T2-weight MRI images achieved excellent correlations with manual quantification (r = 0.98; p < 0.0001) and invasive knee aspiration (r = 0.88; p = 0.0008).40 It was also reported that manual calculation had excellent inter-observer reliability (r = 0.935; p < 0.0001).40 However, the evidence of using MRI to measure of knee effusion in TKA is still lacking.
Figure 4. 3D scanning of lower limb in sitting position using Spectra™ version 3.0 (Vorum Inc., Vancouver, Canada) (a) and real-time data displaced by Spectra™ version 3.0 scanner software (b).

Figure 5. T2-weighted MRI of knee in sagittal and axial view showing hyperintense signals at suprapatellar pouch.
Discussion

The principle and validation studies of various methods of knee swelling measurement have been discussed (Table 1). Traditionally, water displacement is considered the gold standard for limb volumetry. It lacks the ability to truly measure knee effusion volume, which a gold standard should only measure knee synovial fluid volume with the ability to differential such volume against the change of soft tissue volumes such as muscle volume. Hence, in case of post TKA when there would be a significant change of muscular volume, even though water displacement can truly reflect the limb or knee swelling volume, it should not be considered as the gold standard for measuring post TKA effusion volume.

Clinically, the most used knee swelling measurement is girth measurement. Unlike water displacement, circumferential measurement is a quick and simple tool with high

Table 1. Summary of clinically applicable non-invasive methods of measurement of knee swelling.

| Measurement method       | Mechanism                                           | Aim of measurement | Evidence                                                                 | Reliability (Intra-tester ICC; Inter-tester ICC) | Correlation with knee volume measurements (method compared) |
|--------------------------|-----------------------------------------------------|--------------------|--------------------------------------------------------------------------|--------------------------------------------------|----------------------------------------------------------|
| Single Girth Measurement | Girth at target level                               | Swelling           | 1 cm reduction in circumference equivalent to around 40 mL of fluid aspirated | 0.99: 0.98–0.99                                  | Not found                                                |
| Multiple Girth Measurement | Multiple girth for a frustum formula calculation   | Swelling           | Frustum formula is more appropriate in establishing limb volume among a variety of mathematical volume formulae | 0.99: 0.97–0.99                                  | r = 0.86–0.87 (water displacement)                        |
| Water Displacement       | Measuring the volume of water displaced when inserting a limb into water tank | Swelling           | Gold standard for limb volumetry                                         | 0.82: 0.69–0.83                               | Regard as gold standard for limb volumetry               |
| Bioimpedance Spectroscopy| Any edema in a limb can be reflected by a decrease in impedance | Swelling           | Theoretically, current at zero frequency travels only through the extracellular compartment and the impedance measured reflects the volume of edema | 0.90–0.99: 0.89–0.99 | r = 0.73 (frustum model)                                |
| Ultrasound               | Measurement of the maximal anteroposterior width of suprapatellar region | Effusion only      | 30° knee flexion is the most sensitive position for detecting synovial fluid in knee joints | Not found                                       | Not found                                                |
| Perometer                | Infrared light emitting diodes and sensors to determine the vertical and horizontal diameter of the measured limb for volume calculation | Swelling           | Test in measuring upper limb lymphoedema and knee volume                 | 0.99: Not found                                     | r = 0.94 (water displacement)                            |
| Handheld 3D scanner      | Light sensors and motion tracking devices to calculate the 3D coordinates from the returned patterns of light | Swelling including effusion and muscle volume | Tested in measuring knee volume in anterior cruciate ligament reconstruction | >0.8: >0.832                                      | Not found                                                |
| Magnetic resonance imaging| Metallic artifact optimizing software and 3-D volume rendering program for knee synovial volume estimation | Effusion and soft tissues’ volume | Tested in measuring knee effusion volume in cadaveric study and knee osteoarthritis patients | Manual: 0.94: Not found                      | Al: r = 0.88 (knee aspiration)                          |
reliability and minimal infection risk. Guex and Perrin (2000) argued that a measurement of volume should not be estimated by a single circumferential measurement. Multiple girth measurement was developed and gradually replaced water displacement to be a surrogate of actual limb volume measurement in recent studies as it had been shown to correlate well with water displacement in lower limb and knee volume measurement. However, one must note its major limitation that it also fails to differentiate between effusion and edema and serial monitoring using this measurement method for knee swelling for patient after TKA requires careful interpretation. Perometer had also been demonstrated to correlate well with water displacement, however, this use of this expensive stationary device may become less common in knee measurement now due to the advancement in mobile optometric measurement technology.

The most accurate non-invasive method to detect knee effusion volume would be MRI. It has demonstrated to have a good correlation with the result of direct knee aspiration. It is also the only tool that can precisely measure knee synovial fluid volume and muscle volume separately. However, the use of MRI after TKA is often reserved for diagnosing infection, implant loosening, wear and malalignment. Cost effectiveness would be an issue if it is used primarily for detecting and serial monitoring knee effusion that may last for more than 90 days. Besides cost, evidence on validity of MRI with metallic artifact reduction sequence and 3-D volume rendering programs for post-TKA knee effusion measurement is still lacking. Therefore, the implementation of MRI for post-TKA knee effusion monitoring has yet to be justified.

Recently developed methods such as bioimpedance spectroscopy and handheld 3D scanning are also able to estimate knee swelling volume. These methods have the potential to become an accurate and easily accessible clinical tool for knee swelling measurement after TKA and can easily replace the currently used clinical assessment of knee swelling to provide a more detailed and objective measurements for serial monitoring of knee swelling, potentially to aid monitoring of the rehabilitation progress. For instance, a swelling reference chart was developed using bioelectrical impedance assessments on 56 patients after total knee arthroplasty and it aimed to facilitate individualized and real-time adjustment of treatment plans targeting knee swelling based on precise measurement and comparison of patient’s knee swelling volume in reference to others. However, more research is needed for this establishment. For example, diverse arrangements of the placement of electrodes have been documented. Pichonnaz et al. (2013) recommended using a four-wire measurement method with one electrode placed on the most distal girth measurement level of the leg, one on the most proximal girth measurement level of the thigh on each side and one inner electrode at 12 cm above the most distal leg electrode of the measured thigh. On the other hand, Pua (2015) adopted the three-electrode method, with an electrode on the dorsal surface of the third metatarsal midway between the ankle malleoli on each lower limb and a reference electrode placed on the right dorsal surface of the third metacarpal midway between the styloid processes. It is, however, unclear if the position of electrode placement has any effect on the indirect estimation of edema volume. As for 3D scanning, there is a study attempting to measure knee effusion volume and muscle volume separately by measuring the volume of identified knee regions. This indirect measurement does not represent the internal anatomy of the knee and further research is required to determine the association of the volume of identified knee region such as the patella region with actual swelling volumes. Moreover, 3D scanning requires advanced software, time and technical support to obtain volume measurement. Despite being able to obtain scans in seconds, the time to process the scan is long and should be addressed before clinical implementation. The development of a fully automated program for volume measurement in the future will certainly improve the clinical utility of handheld 3D scanners.

Conclusion

The clinically applicable non-invasive measurements of knee swelling have been reviewed. Circumferential measurement is simple and reliable; however, operator must notice its substantial bias to inaccurate effusion volume estimation. The limitations of volumetric measurement undermined their potential as a clinically applicable and accurate tool for knee swelling volume measurement. Magnetic resonance imaging offers soft tissue and synovial fluid volume differentiate and precise measurement. New metal artifacts reduction sequence and automatic effusion quantification programs are emerging. Bioimpedance spectroscopy and 3D scanning offer quick and precise quantification of knee swelling volume. 3D scanning can also perform differential measurement of knee swelling and can be a future for swelling volume and effusion estimation. Further research should be conducted to validate 3D scanning measurements in correlation to knee effusion volume to establish an accurate, reliable and easily accessible clinical tool for knee swelling and effusion measurement that will aid monitoring and guiding of post-TKA management.

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KY Li searched literature and drafted the manuscript. Henry FU developed the idea for the study and revised the manuscript. MH Cheung, VWK Chan, A Cheung, PK Chan and KY Chiu involved in editing the manuscript. The authors read and authorized the final manuscript for publication.

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**Appendix**

**Abbreviations**

AC Alternating current

BIS Bioimpedance Spectroscopy

ICC Intraclass correlation coefficient

MRI Magnetic resonance imaging

OA Osteoarthritis

SEMAC Slice-Encoding for Metal Artifact Correction

SPACE Sampling Perfection with application optimized contrast using different angle evolutions

TKA Total knee arthroplasty

TKR Total knee replacement

T2W T2 weighted turbo spin echo

VAT View Angle Tilting

3D Three Dimensional