Improve your surgical drilling skills, make use of your index fingers.

Aernout R.J. Langeveld [1*], Christine M.E. Rustenburg [2,3], Marco J.M. Hoozemans [3,4], Duncan E. Meuffels [5], Bart J. Burger [6]

* A.R.J. Langeveld, MD, Department of Orthopaedic Surgery, HagaZiekenhuis, Els Borst-Eilersplein 275, 2545 AA Den Haag, The Netherlands (email: aernoutlangeveld@gmail.nl)

Author details

[1] Department of Orthopaedic Surgery, HagaZiekenhuis, The Hague, The Netherlands

[2] Department of Orthopaedic Surgery, VU University Medical Centre, Amsterdam, The Netherlands

[3] Amsterdam Movement Sciences, Amsterdam, The Netherlands.

[4] Faculty of Behavioural and Movement Sciences, Department of Human Movement Sciences, Vrije Universiteit Amsterdam, The Netherlands

[5] Department of Orthopaedic Surgery, Erasmus MC, University Medical Centre, Rotterdam, The Netherlands

[6] Department of Orthopaedic Surgery, Noordwest Ziekenhuisgroep, Alkmaar, The Netherlands

Abstract

Background: Over the past decades, surgery has greatly benefited from various technological advancements. Still, surgery remains, in essence, manual labour performed by well-trained surgeons. So far, little research has focused on improving osseous drilling techniques. The objective of this study was to compare the accuracy and precision of different orthopaedic drilling techniques involving the use of both index fingers and to investigate whether the effect of drilling technique on accuracy and precision is affected by the level of experience of the performer.

Methods/design: We included a total of 36 participants from two Dutch training hospitals, which were distributed equally over three groups, based on their surgical experience. The participants were instructed to drill towards a target exit point on a surrogate bi-cortical bone, using a pistol-grip cordless drill with similar technical specifications and shape as used during surgery. Accuracy (i.e. systematic error) and precision (i.e. random error) of the actual exit points compared to target exit points were analysed using mixed design ANOVAs.

Results: Different drilling techniques significantly affected accuracy ($p<0.01$). A shooting grip with aiming at the index finger and a clenched grip with aiming at the index finger both improved accuracy compared to a clenched grip without aiming at the index finger (both $p<0.01$) and a shooting grip without aiming at the index finger ($p=0.01$ and $p=0.02$, respectively). There was a significant effect of drilling technique for precision ($p=0.02$). A shooting grip with aiming significantly outperformed the clenched grip without aiming ($p=0.02$). The three groups, differing in surgical experience, were not comparable in accuracy and precision. Orthopaedic surgeons (i.e. >6 years of orthopaedic drilling experience) outperformed the inexperienced group (i.e. no orthopaedic drilling experience) in both accuracy and precision ($p=0.01$ and $p<0.01$, respectively). However, the interaction between surgical experience and drilling technique was not significant, showing that differences between drilling techniques are not affected by surgical experience.

Conclusion: Based on this study, a shooting grip with aiming towards the index finger of the opposite hand has a significant better outcome in both accuracy and precision compared to a clenched grip alone. The clenched grip combined with aiming towards the index finger also tends to have a superior effect as compared to the one hand clenched grip only. Differences between drilling techniques are not affected by experience, but experienced surgeons outperformed less experienced participants. Based on our study we advise the surgeon to aim at the index finger of the opposite hand where possible and to align the ipsilateral index finger to the drill bit.

Introduction

Surgical care is a main element of the healthcare process. Good surgical techniques are of vital importance to improve outcome and reduce complications [1]. Surgery has greatly benefited from various technological innovations over recent decades, but it is still very much manual dexterity [2]. Human error in surgery is impossible to overcome and is a known risk factor for inaccurate bone drilling, cutting and removal of hardware [3]. Some surgeons are naturally dexterous, others through repetition and practice achieve an acceptable level by the end of their training [4][5]. Some additional operative skills are mandatory for orthopaedic surgeons. Drilling of bone is a skill that is learned *in vivo* over years during most surgical training programs, without specific emphasis. Vital structures near the bone and often-limited space to position screws, wires or sutures allow little room for error [6]. In training hospitals, the surgeon responsible for the operation often takes over from his trainee when such a crucial drilling moment arises. This might limit the development of drilling dexterity in trainees. The development of this specific orthopaedic skill may actually be successfully trained outside theatre in a simulation-based training environment [7][8][9][10]. Moreover, a slight change of technique is easy to implement during surgery and might also improve drilling outcome, leading to less intraoperative iatrogenic damage.

Different grip of the orthopaedic drill

Aimed point shooting is a technique that has been used and discussed for using handguns since the early 19th century [11]. This method of shooting a firearm does not rely on aiming the gun by the use of sight. The index finger is able to point instinctively and accurately at objects. This is likely due to anatomical factors. The index finger has a separate extensor tendon (i.e. extensor indicis), and therefore it can be moved more independently from the adjacent fingers [12]. The assumption is that more accurate aiming with a pistol is achieved if one employs the index finger to aim the gun and the middle finger to pull the trigger (shooting grip). This theory was tested and the technique was proven to be more accurate [13]. We extrapolated this knowledge to predict that the shooting grip of the surgical drill hand piece might make aiming more accurate and precise.

Index finger of the opposite hand

Gaze behaviour and eye hand coordination have been examined extensively in challenging visual motor tasks [14]. Orthopaedic drilling is a challenging visual motor task, since the exit point of the bone is often not visible. This complex goal-targeted movement may be improved by the use of proprioception of the index finger of the opposite hand, as it is rather easy to find your other index finger with your eyes closed due to proprioception, providing a narrower and more resolute frame of reference [15]. Several studies have shown that we are able to represent the location of objects with respect to our own body and especially to our hands [15–19].

For these reasons, we predict for drilling in bone during orthopaedic surgery that positioning the index finger of the opposite hand just behind the aimed exit point will improve outcome due to the benefit of proprioception when there is no visual information. Furthermore, iatrogenic lesions due to overshoot might decrease due to the sensory feedback of the nearly penetrated bone, which can easily be felt at the tip of the surgeon's finger.

The primary objective of this study was to examine the effect of drilling technique (i.e. the shooting grip technique and the use of the index finger of the opposite hand) on the accuracy (i.e. systematic error) and precision (i.e. random error) in orthopaedic drilling. Furthermore, we hypothesized that experienced surgeons have less difficulty with changing their technique than inexperienced participants as surgeons already have a high level of drilling dexterity.

Therefore, our secondary objective was to investigate whether the effect of drilling technique on accuracy and precision is affected by the level of experience of the performer.

Methods

Study design and study population

A total of 36 subjects participated in the experimental study, which was conducted at two hospitals in the Netherlands: one university hospital and one large teaching hospital. Eighteen members from both hospitals volunteered for participation, to eventually arrive at three groups of equal size. These groups consisted of: 1) orthopaedic surgeons (Group OS; >6 years of drilling experience), 2) orthopaedic residents (Group OR; <6 years of drilling experience) with 2-6 years of orthopaedic training and 3) persons with no practical orthopaedic experience (Group IE, e.g. researchers and medical interns; no drilling experience). The study was approved by our hospital's review board committee.

Experimental set-up

Drilling exercises were performed on standardized surrogate bi-cortical bone (sawbones). One set of sawbones, consisting of one tibia and one femur, was prepared per participant to complete all the drilling exercises. Each sawbone was pre-marked in the same way. Both starting point and aiming point consisted of black dot with a diameter of 3mm, surrounded by a colour matching the different techniques. The drilling trajectories and length of the trajectories (i.e. 3 cm) was the same for every sawbone. A pistol grip cordless drill with the similar technical specifications, weight and outline as used in theatre (Metabo Powermaxx BS Basic, 10.8 V, 2 Ah, max. 1300 rpm) was used, with a standard AO surgical drill bit (i.e. 2.5mm diameter).

Procedure

The four experimental drilling techniques were explained, illustrated by an image (Figure 1). The first technique ('red') did not involve a different grip or use of the index finger of the opposite hand; the second technique ('blue') only involved a different grip (shooting grip) but not the use of the index finger of the opposite hand; the third technique ('green') did not involve a different grip but the index finger of the opposite hand was used; and lastly, the fourth technique ('orange') involved both the shooting grip and the use of the index finger of the opposite hand.

Following the instructions, participants were asked to start drilling at the starting point and to exit the bone as near to the marked aiming point as possible. Each participant followed the same sequence (i.e. blue after red, orange after blue, green after orange, red after green), but to prevent an advantage per technique, each participant had a different starting point in the sequence with a counterbalanced design for the number of starting conditions within each group.

The participants were allowed to drill a pilot hole at the starting point and have a look at the aiming point. Once they had started drilling, they were not allowed to have another look at the aiming point. The same researcher (CR) was present at all tests. Each drilling technique had to be applied five times per set of femur and tibia (i.e. 20 drill trajectories per test). To account for a possible test effect the procedure was repeated after four weeks, preserving the counterbalanced design for the number of starting conditions.

Data acquisition and analyses

The experimental procedure resulted in five drilling holes per drilling technique per participant per session. The distances of the locations of the actual exit points of the five drilling holes in relation to the target exit point were used to determine the accuracy and precision of each attempt for each participant.

Since the shape of the exit point was most of the time oblique instead of round, we calculated the distance between the actual exit point and the target exit point by taking the sum of the distance between the centre of the target and the inner (nearest) border of the drilling hole and the centre of the target and the outer (farthest) border of the drilling hole, divided by two (Figure 2). We used a calliper to assess the distances (Figure 2). The same researcher (CR) performed each assessment to prevent any interobserver variability.

Distances between actual exit point and target exit point were used to determine the accuracy and precision of the drilling technique. Accuracy was defined as systematic error (SE) and calculated as the mean of the five distances between the five exit points and the target exit point. Precision was defined as random error (RE) and calculated as the standard deviation of the five distances between the five exit points and the target exit point.

Sample size calculation

An accuracy of less than 2mm was considered adequate. This is in line with what is generally acknowledged in literature[20]. With a power of 80% and an alpha of 0.05, to detect a systematic difference of 2 mm between the exit point and the target exit point with a measurement error of 1 mm [20], a minimum of 18 participants were required, using a mixed design ANOVA with the three experience groups and the four techniques as independent variables.

Statistical analyses

The effect of drilling technique (clenched grip, shooting grip, aiming at index finger) on the accuracy and precision of orthopaedic drilling was examined with a four-way mixed design

ANOVA. Drilling technique and repetition (first and second session) were included as within subjects factors and hospital (university and teaching) and experience (orthopaedic surgeon, orthopaedic resident, inexperienced) were included as between-subjects factors. Pairwise comparisons with Bonferroni correction were performed to examine differences between drilling techniques. One-way within- and between-subjects ANOVAs with Bonferroni correction were used to examine the interaction effects if significant. Partial eta squared (η_p^2) was used to determine the effect size. The assumption of normality was checked by visual inspection of histograms, q-q plots and box plots of the data within the groups. Shapiro-Wilks tests were also performed on the data. Most of the precision data appeared not to be normally distributed, therefore all precision data were transformed using a reciprocal transformation (by dividing one by each score after adding 5 mm) on all precision data before statistical analyses. The assumption of sphericity was checked according to Girden (1992). With a Greenhouse-Geisser epsilon ≥0.75, the Huynh-Feldt correction was used, otherwise the Greenhouse-Geisser correction was used. Homogeneity of variance was checked using Levene's test and this assumption was not violated. All statistical analyses were performed using IBM SPSS 22.0 (IBM Software, Armonk NY, USA) and a p-value <0.05 was considered to be statistically significant.

Results

Accuracy

We defined accuracy as the systematic error of all measurements (i.e. the systematic difference in distance between the actual exit point and the target exit point).

There was a significant main effect of different drilling techniques for accuracy, $F(3.0,90.0)=8.77$, $p<0.01$, $\eta p^2=0.23$. Pairwise comparisons showed that accuracy was improved when using a shooting grip with aiming at the index finger (mean distance 4.12

mm, SD 1.17) as well as a clenched grip with aiming at the index finger (mean distance 4.04 mm, SD 1.11) was compared to a clenched grip without aiming at the index finger (mean distance 4.98 mm, SD 1.19) (both $p<0.01$) as well as compared to shooting grip without aiming at the index finger (mean distance 4.90 mm, SD 1.36) ($p=0.01$ and $p=0.02$, respectively). The interaction between drilling technique and experience appeared not to be significant ($F(6.0,90.0)=0.61$, $p=0.72$, $\eta p^2=0.04$) but there was a significant main effect of experience level for accuracy, $F(2.0,30.0)=5.10$, $p=0.01$, $\eta p^2=0.25$. Post-hoc tests showed that orthopaedic surgeons outperformed the inexperienced group ($p=0.01$), with a mean difference of 0.95 mm. There was no significant main effect of hospital or repetition observed, and the effect of technique on the accuracy of drilling appeared not to be depended on hospital and repetition as significant interactions were not observed.

Precision

Precision was defined as the random error of all measurements (i.e. the random difference in distance between the actual exit point and the target exit point). The main effect of different drilling techniques was significant with $F(3.0,90.0)=3.66$, $p=0.02$, $\eta p^2=0.11$. The technique with the shooting grip with aiming at the opposite finger (median 1.97 mm, IQR 1.19) significantly outperformed the clenched grip without aiming at the opposite finger (median 2.87 mm, IQR 1.07) ($p=0.02$). There were no significant effects for the shooting grip without aiming at the opposite finger (median 2.24 mm, IQR 1.37) and the clenched grip with aiming at the opposite finger (median 2.37 mm, IQR 1.31). However, the main effect of level of experience appeared to be significant ($F(2.0,30.0)=5.76$, $p<0.01$, $\eta p^2=0.28$). Orthopaedic surgeons (median 2.21 mm, IQR 1.02) appeared to be able to drill more precise compared to the inexperienced group (median 2.79 mm, IQR 1.38) ($p<0.01$). For precision, other significant main effects as well as significant interactions were not observed.

Discussion

Safe surgery is advocated by the World Health Organization [21]. The operating surgeon and his team have the responsibility to execute a safe operation. Good surgical techniques are cherished, as they can prevent iatrogenic damage.

The main idea behind this study is to help surgeons get better intraoperative drilling results through some practical changes in their technique. Our team thought of four different drilling techniques, involving the index finger of both hands. We expected that the technique combining the use of both index fingers leads to the best results. The objective of the study was, therefore, to examine the accuracy and precision of different orthopaedic drilling techniques. Our research showed that accuracy and precision in drilling are improved by putting the index finger in line with the drill bit and using the middle finger to pull the trigger while drilling towards the index finger of the opposite hand. Further, senior surgeons with more than six years of orthopaedic drilling experience had significantly better outcomes compared to inexperienced individuals in both accuracy and precision, indicating that experience does matter.

Targeted movements such as drilling are guided by proprioceptive and visual information gathered by the brain. The cerebellum is likely to compare intended movements with actual ones and make the necessary corrections [22]. Controlled movements occur in combination with the vestibular system. The distinct areas responsible for targeted movement on the human brain have been mapped. In a functional MRI study by Makin et al., specific areas of the brain (i.e. intraparietal sulcus and lateral occipital complex) were identified representing nearby visual space with respect to the hands (i.e. perihand space) [17]. In the somatosensory homunculus, the hand has the biggest proportion of all body parts on the primary motor and sensory cortex. This reflects tactile experience, voluntary movement and kinaesthetic proprioception [23]. The presentation of the fingertip in the somatosensory homunculus expands with tactile experience [24]. Due to different innervation density, the fingertip has more tactile potential than the base of the finger [25]. Many surgeons only rely on visual information and the proprioceptive information of the drilling hand. Proprioception may thus be improved by additional proprioceptive information from the index finger of the drilling hand as well as the index finger of the opposite hand.

There is little research on the actual practice of drilling. Most of the current literature focusses on the mechanical aspects of the drills used. Thermal injury due to drilling is a well-accepted problem that may lead to osteonecrosis [26–28]. Necrosis around the osteosynthesis screws causes secondary loosening, causing the construct to fall apart [29]. There is no consensus on bone drilling speed and force, but most of the experimental studies advice high speed and larger force to minimise temperature formation [29]. Many practical aspects of our profession could not be retrieved from literature. Advice on the drilling techniques used by senior surgeons is mostly anecdotal and based on trial and error. Some advocate the ‘woodpecker drilling technique’ in which you give small punches while drilling, and the feedback felt in the hand piece will tell how much you have penetrated the bone and if you have passed the opposite cortex. Others say they can feel the speed go up just before the second cortex is crossed as the resistance offered by the bone wanes towards the end. Senior tips on aiming vary. Holding the elbow firmly to the side of the body and having both hands attached to the hand piece could secure a more stable situation resulting in more accuracy and precision, when tracking a small target, research participants increase muscle activity of the extremity and pressure of their grip [30]. Most people favour one hand due to cerebral laterality. This dominant hand is more precise and faster, but even with the dominant hand there is a small systemic aiming bias during drilling [3].

Although experience of the performer did not affect the effect of drilling technique, this study confirms that skilled orthopaedic surgeons outperform inexperienced candidates. This suggests that long-term experience in bone drilling does help obtaining good results and that repetitive drilling of bone improves outcome despite the lack of a short-term learning curve. Practicing one's techniques might speed up the time needed to obtain an acceptable and safe level of drilling in real-life circumstances. At the same time, using both index fingers at the same time seemed to be more complex than expected and some participants were unable to master this combination. We expect that as they get more accustomed, the combination will eventually lead to superior drilling results. Therefore, we advise first getting comfortable with drilling towards the tip of the finger of the opposite hand. When this starts feeling natural, it is recommended to implement the shooting grip technique in clinical settings.

This study has some limitations. First, the individuals performing the drilling tasks had to work with sawbones instead of fresh frozen human cadavers, which gives different feedback felt in the drill due to the plastic material (i.e. softer) compared to bone (i.e. harder), which may affect outcomes since surgeons and residents are more used to drilling in harder materials. However, since all tests were performed on sawbones, we do not expect that this altered the results or conclusion of this study. Second, the tests were performed on sawbones with no surrogate soft tissue present. It was therefore easy to position one's index finger at the exit point, which may be more difficult or even impossible *in vivo* due to the soft tissue surrounding the bone. In such cases, there is not enough physical space available to position the surgeon's finger, making it impossible to aim at the opposite index finger. However, aligning the ipsilateral index finger to the drill bit may still be possible in these cases. Third, the test environment was different from real-life situations in which the physician is more focussed and takes more time per drilling trajectory to prevent iatrogenic damage. As this may affect the intrapersonal variability, we believe that this does not affect the interpersonal variability and therefore, does not have an effect on the outcomes of this study. Last, with our proposed technique, it is not possible to secure drill sleeves after the drill grips. Drill sleeves protect the soft tissue and help to position the drill until it grips, centring the drill bit in an osteosynthesis plate. Sparrow et al. correctly mention that lifting or pushing the drill sleeve alters the trajectory [3]. When the surgeon aims at the index finger of his opposite hand, there is no hand left to hold the drill sleeve. In most cases, this problem may be overcome by the assistant who helps to protect the soft tissue.

Conclusion

The goal of this *in vitro* study is to help surgeons get better intraoperative drilling results through some practical changes in their technique. Using a different grip of the drill that involves the use of the ipsilateral index finger to aim (i.e. shooting grip) while drilling towards the index finger of the opposite hand, turns out to be more accurate and precise than holding the drill with four clenched fingers and not using the opposite hand. A clenched grip while aiming at the index finger of the opposite hand improved accuracy compared to both a shooting and clenched grip without aiming. Therefore, we advise that, where possible, the surgeon aims at the index finger of the opposite hand positioned just behind the ideal exit point of the bone. When this feels comfortable after some practice, she or he could also align the ipsilateral index finger to the drill bit.

References

1 WHO. WHO Guidelines for Safe Surgery 2009 - Safe Surgery Saves Lives. WHO/IER/PSP/2008.08-1E. *Second Glob Patient Saf Chall* 2009;:133. doi:January 13, 2013

2 Camarillo DB, Krummel TM, Salisbury JK. Robotic technology in surgery: Past, present, and future. Am. J. Surg. 2004;**188**. doi:10.1016/j.amjsurg.2004.08.025

3 Sparrow T, Heller J, Farrell M. In vitro assessment of aiming bias in the frontal plane during orthopaedic drilling procedures. *Vet Rec* 2015;**176**:412. doi:10.1136/vr.102977

4 Sturm LP, Windsor JA, Cosman PH, *et al.* A Systematic Review of Surgical Skills Transfer After Simulation-Based Training. *Ann Surg* 2008;**248**:166–79. doi:10.1097/SLA.0b013e318176bf24

5 Barnes RW. Surgical handicraft: Teaching and learning surgical skills. *Am J Surg* 1987;**153**:422–7. doi:10.1016/0002-9610(87)90783-5

6 Sinha a, Edwin J, Sreeharsha B, *et al.* A radiological study to define safe zones for drilling during plating of clavicle fractures. *J Bone Joint Surg Br* 2011;**93**:1247–52. doi:10.1302/0301-620X.93B9.25739

7 Hohn E a., Brooks AG, Leasure J, *et al.* Development of a Surgical Skills Curriculum for the Training and Assessment of Manual Skills in Orthopedic Surgical Residents. *J Surg Educ* 2014;**72**:47–52. doi:10.1016/j.jsurg.2014.06.005

8 Sewell C, Blevins NH, Peddamatham S, *et al.* The effect of virtual haptic training on real surgical drilling proficiency. *Proc - Second Jt EuroHaptics Conf Symp Haptic Interfaces Virtual Environ Teleoperator Syst World Haptics 2007* 2007;:601–3. doi:10.1109/WHC.2007.111

9 Tsai MD, Hsieh MS, Tsai CH. Bone drilling haptic interaction for orthopedic surgical simulator. *Comput Biol Med* 2007;**37**:1709–18. doi:10.1016/j.compbiomed.2007.04.006

10 Vankipuram M, Kahol K, McLaren A, *et al.* A virtual reality simulator for orthopedic basic skills: A design and validation study. *J Biomed Inform* 2010;**43**:661–8. doi:10.1016/j.jbi.2010.05.016

11 Lt. Col. Baron De Berenger. *Helps And Hints - How To - Protect Life And Property*. 1835.

12 Ross LMED, editor. Thieme Atlas of Anatomy: General Anatomy and Musculoskeletal System. 2006. 58890.

13 Walter J. Dorfner. *Point Shooting - The Next Step in the Evolution of Survival Shooting?-*. 1999.

14 Sailer U, Flanagan JR, Johansson RS. Eye-hand coordination during learning of a novel visuomotor task. *J Neurosci* 2005;**25**:8833–42. doi:10.1523/JNEUROSCI.2658-05.2005

15 Brown LE, Marlin MC, Morrow S. On the contributions of vision and proprioception to the representation of hand-near targets. *J Neurophysiol* 2015;**113**:409–19. doi:10.1152/jn.00005.2014

16 Làdavas E, Farnè a, Zeloni G, *et al.* Seeing or not seeing where your hands are. *Exp Brain Res* 2000;**131**:458–67. doi:10.1007/s002219900264

17 Makin TR, Holmes NP, Zohary E. Is that near my hand? Multisensory representation of peripersonal space in human intraparietal sulcus. *J Neurosci* 2007;**27**:731–40. doi:10.1523/JNEUROSCI.3653-06.2007

18 di Pellegrino G, Làdavas E, Farné A. Seeing where your hands are. *Nature* 1997;**388**:730. doi:10.1038/41921

19 Brown LE, Morrissey BF, Goodale MA. Vision in the palm of your hand. *Neuropsychologia* 2009;**47**:1621–6. doi:10.1016/j.neuropsychologia.2008.11.021

20 Meuffels DE, Reijman, M Verhaar J. Computer-Assisted Surgery Is Not More Accurate or Precise Than Conventional Arthroscopic. 2012;:1538–45.

21 Haynes AB, Weiser TG, Berry WR, *et al.* A surgical safety checklist to reduce morbidity and mortality in a global population. *N Engl J Med* 2010;**35**:491–9.

22 Henriques DYP, Filippopulos F, Straube A, *et al.* The cerebellum is not necessary for visually driven recalibration of hand proprioception. *Neuropsychologia* 2014;**64**:195–204. doi:10.1016/j.neuropsychologia.2014.09.029

23 Penfield W, Boldrey E. Somatic motor and sensory representation in the cerebral cortex of man as studied by electrical stimulation. *Brain* 1937;**60**:389–443. doi:10.1093/brain/60.4.389

24 Peters RM, Hackeman E, Goldreich D. Diminutive digits discern delicate details: fingertip size

and the sex difference in tactile spatial acuity. *J Neurosci* 2009;**29**:15756–61. doi:10.1523/JNEUROSCI.3684-09.2009

25 Gibson GO, Craig JC. Relative roles of spatial and intensive cues in the discrimination of spatial tactile stimuli. *Percept Psychophys* 2002;**64**:1095–107. doi:10.3758/BF03194759

26 Natali C, Ingle P, Dowell J. Orthopaedic bone drills-can they be improved? Temperature changes near the drilling face. *J Bone Joint Surg Br* 1996;**78**:357–62.

27 Bertollo N, Walsh WR. Drilling of Bone: Practicality, Limitations and Complications Associated with Surgical Drill-Bits. *Biomech Appl* Published Online First: 2011.http://www.intechopen.com/books/biomechanics-in-applications/drilling-of-bone-practicality-limitations-and-complications-associated-with-surgical-drill-bits

28 Augustin G, Zigman T, Davila S, *et al.* Cortical bone drilling and thermal osteonecrosis. *Clin Biomech* 2012;**27**:313–25. doi:10.1016/j.clinbiomech.2011.10.010

29 Pandey RK, Panda SS. Drilling of bone: A comprehensive review. *J Clin Orthop Trauma* 2013;**4**:15–30. doi:10.1016/j.jcot.2013.01.002

30 Huysmans MA, Hoozemans MJM, van der Beek AJ, *et al.* Submovement Organization, Pen Pressure, and Muscle Activity Are Modulated to Precision Demands in 2D Tracking. *J Mot Behav* 2012;**44**:379–88. doi:10.1080/00222895.2012.727916

Figure 1. Overview of all techniques.

Red The dominant hand holds the drill with four fingers clenched, without aligning the ipsilateral index finger (clenched grip).

Blue The dominant hand holds the drill with three fingers clenched, and the index finger is used to help guide the trajectory (shooting grip).

Green Clenched grip by the dominant hand. The index finger of the opposite hand is put at the aiming point and used to aim at.

Orange Shooting grip by the dominant hand. The index finger of the opposite hand was put at the aiming point and used to aim at.

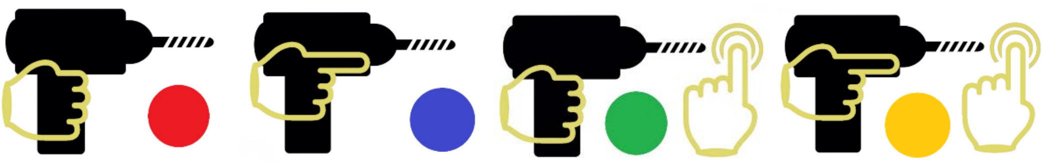

Figure 2. The assessment of the distance towards the targeted exit point, using a calliper.

Distance is marked as A (in mm). It measures the centre of the targeted drilling exit point (black dot in red circle) to the centre of the actual drilling exit point (black plus in yellow ellipse). To minimize measurement error, the distance for each exit point is measured by taking the sum of the distance between the centre of the target and the inner (nearest) border of the drilling hole and the centre of the target and the outer (farthest) border of the drilling hole, divided by two (A=(B+C)/2). All measurements were in millimetres (mm) and all measurements were done by the same researcher (CR), using the same calliper.

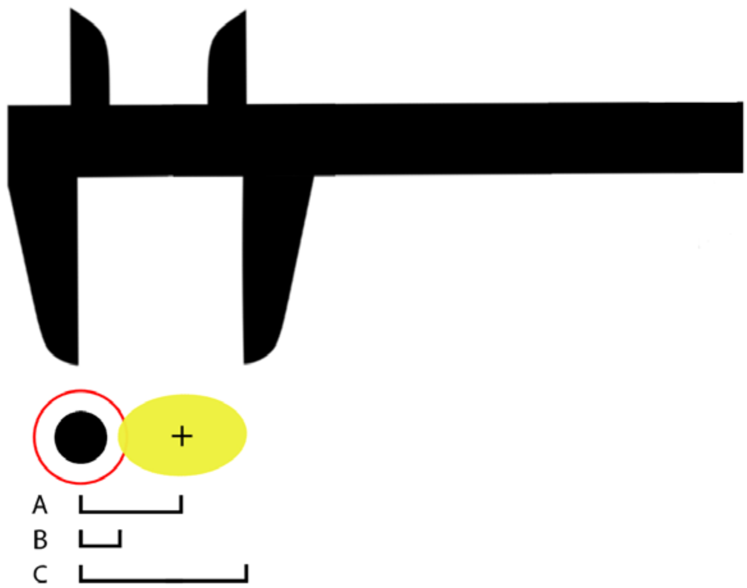

Figure 3. Overview of drilling accuracy.

An overview of the results of accuracy in drilling, expressed as the mean distance (mm) between the exit point and the target. Accuracy was defined as the systematic error. CG-: Clenched grip without the use of the index finger of the opposite hand; SG-: Shooting grip without the use of the index finger of the opposite hand; CG+: Clenched grip with the use of the index finger of the opposite hand; SG+: Shooting grip with the use of the index finger of the opposite hand. Error bars indicate one standard deviation.

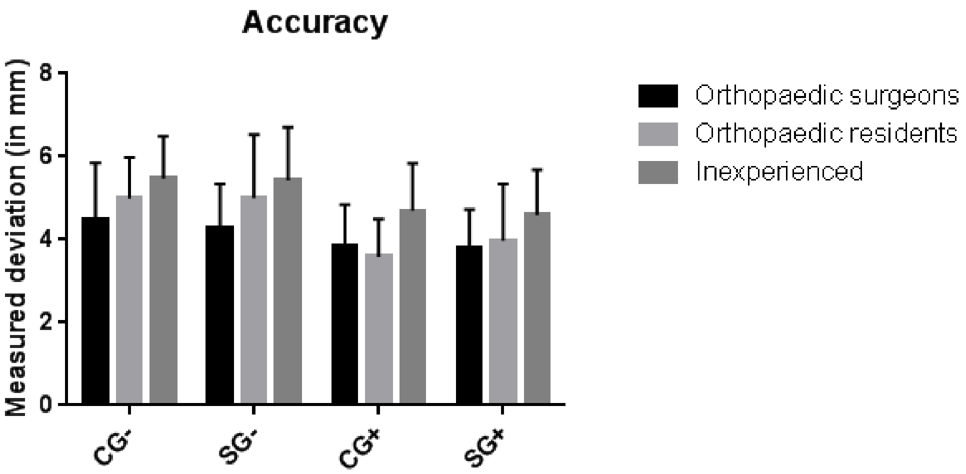

Figure 4. Overview of drilling precision.

An overview of the results of precision in drilling. Data of precision are visualized as boxplot and precision was defined as the random error, and expressed as the mean standard deviation of the distances (mm) between the exit points and the target. CG-: Clenched grip without the use of the index finger of the opposite hand; SG-: Shooting grip without the use of the index finger of the opposite hand; CG+: Clenched grip with the use of the index finger of the opposite hand; SG+: Shooting grip with the use of the index finger of the opposite hand.