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Measurement of Surgical Dexterity Using Motion Analysis of Simple Bench Tasks

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Abstract. The possibility of using quantitative motion analysis for objective assessment of simple surgical dexterity is investigated using the Imperial College Surgical Assessment Device (ICSAD) with qualitative analysis undertaken by inspection. Bench-top knot tying and suturing skills were performed and examined for the ability to discriminate between surgeons of varying experience. These exercises were found to discriminate significantly between junior and senior surgeons in terms of both time taken and the number of movements required. The relation between time and motion was found to be variable depending on what skill was being undertaken: simple suturing, suturing at depth, or knot tying (1.71 vs. 1.86 vs. 2.36; $p =$ 0.002 for 1 vs. 2; $p < 0.001$ for others). When the number of movements in a minute (standardized movements per minute) were considered, both groups were found to work at a similar rate, depending on the task, implying that the more experienced surgeon is more economical, performing the same exercise with fewer moves rather than with higher speed. Motion analysis exhibits face and construct validity and is a reliable assessment of simple surgical dexterity. Its use for objective assessment of dexterity and competence should be encouraged.

Traditional assessments in surgery have been knowledge based, and any analysis of actual performance has been subjective, with measurements that show poor repeatability and reliability [1–5]. Yet the importance of dexterity and performance in surgeons was recognized at an early stage by Celsus: "A surgeon ought to be in early manhood, or at any rate not much older; have a swift and steady, never faltering hand, and no less skill in the left hand than the right." The need to measure this technical skill and proficiency in surgeons as part of formal competence assessment and revalidation has become increasingly recognized [6–9], especially when previous work has shown that academic achievement and interview techniques do not correlate, or correlate negatively, with surgical skill measured subjectively [10, 11]. Spencer attempted to quantify this operative skill into 75% decision-making, which is based on knowledge and sound judgment, and 25% technical skill, putting dexterity into perspective.

Measuring this task performance in surgery was recognized as being somewhat subjective: "good hands" (suggesting cognitive deficiency), "above average skills" (implying average skills), "appropriate skills" (needs help), or showing "steady improvement" (meaning inept) [12]. Attempts to objectify these assessments of surgery were limited to the time taken to perform the task (i.e., a quantitative measure) [13–15], and some attempts have been made to measure the outcome of the task performed [16] (a qualitative measure). Time measurement is an obvious method for objective assessment [15] and appeals to managers in terms of cost efficiency. However, time pressure can have a detrimental effect on precision and does not guarantee quality: Is the fastest surgeon the best? Work undertaken in laparoscopic surgery has suggested that the learning curve for operator speed is shorter than the learning curve for accuracy and is thus a crude measure of performance [17]. Thus time alone should not be a measure of surgical proficiency. Measurement of manual dexterity has been undertaken in surgeons in the past using devices such as the Perdue pegboard, Minnesota small parts test, or other aptitude tests [18–21]. It has been used both as a method of assessment and an attempt at aptitude testing, although some groups have shown correlations between aptitude tests and actual performance [22–24]. The problem with using tests such as the Perdue pegboard and the Minnesota small parts test is that they predict skills that are required for light industrial work rather than those required by a surgeon.

The use of motion analysis has been pioneered in gait analysis [25]; electromagnetic motion analysis has been used extensively and successfully even for spinal motion analysis [26]. Electromagnetic tracking has the advantage of not requiring line of sight, which is necessary for any visual or infrared-based system. The Imperial College Surgical Assessment Device (ICSAD) allows tracking a dexterity task by electromagnetic means [27]. It measures the time taken, the number of movements, and the path length, all of which measures can be shown to change with experience in laparoscopic surgery [28] and the first two in open surgery [29].

The question therefore arises if it is possible to quantify which surgeons have honed and practiced their skills based on simple dexterity measurements, possibly to determine competence levels. The aim of the study was therefore to investigate whether measurement with motion analysis can discriminate between surgeons of varying experience across a range of simple benchtop surgical tasks to develop construct validity. The relation between time and motion was also explored to determine which is the key measure.

Materials and Methods

Data acquisition was with ICSAD. This motion analysis device uses an alternating current electromagnetic system with passive receiv-

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ers attached to the dorsum of the hand over the mid-shaft of the third metacarpal. As hand movement takes place, a current is induced in the trackers, which is analyzed to determine the position of the hand/tracker. Data acquisition takes place at 20 Hz (rates of up to 100 Hz are possible). These raw positional data are analyzed by Bespoke software and calculate the number of movements, path length, and speed of movements for each hand. Noise is minimized by filtering the data. To calculate parameters, the number of movements for each hand are combined to give a total number of movements. For open surgery, in contrast to laparoscopic surgery, path length has been found to be nondiscriminatory; because this path length or distance traveled is used to calculate hand speed, it is not used for analysis.

The starting point of the experiment was standardized with the trainee's hands on the work station either grasping the suture material or the instruments for suturing. Recording was stopped at placement of the final throw or when the final suture was cut. The experiment was divided into two stages.

Stage 1: Is the relation between time and motion fixed, or does it vary according to the task assessed? Five surgeons were recruited to the laboratory to undertake three surgical tasks whose performance time was similar (approximately 40 seconds). These exercises were repeated 10 times each. The three tasks chosen were as follows.

1. Two interrupted sutures [using 2-0 Surgidac, V-30 needle (USSC)] were placed in a standardized synthetic skin pad (Limbs and Things, marked 1 cm at either side of wound, tied with four instrument-tied throws.
2. Figure-of-eight suture (using 2-0 Surgidac on a V-30 needle) was performed at depth in an Annexe Art jig. The figure-of-eight had four fixed entry and exit points 1 cm apart on a Limbs and Things skin pad with four hand-tied throws.
3. A series of 15 hand-tied throws with 4/0 Prolene were performed "at depth" on an Ethicon knot-tying jig.

Stage 2: Is it possible to discriminate between surgeons of varying experience on simple bench models? Which are the best models and methods? Are more experienced surgeons more economical with their movements? A group of 30 surgeons [16 basic surgical trainees (BSTs) and 14 higher surgical trainees (HSTs)] were recruited to the laboratory to undertake a series of simple tasks divided into knot-tying and suturing stations. All the BSTs had previously attended a basic surgical skills course. The knot tying was undertaken on a standard Ethicon knot-tying jig; and all knot tying was undertaken on the hook in an inverted Perspex cup, replicating knot tying "at depth." Suturing exercises were undertaken on jigs as described. The knot-tying tasks were as follows.

2/0 Biosyn (USSC) (monofilament suture), four throws
4/0 Prolene (USSC) (monofilament suture), four throws (first run)
2/0 Polysorb (USSC) (braided suture), four throws, repeated five times
4/0 Prolene (USSC) (monofilament suture), four throws (second run)
4/0 Prolene (USSC), 10 throws

The suturing exercises were undertaken on synthetic pads (Limbs and Things). All entry and exit points were marked to standardize the task and remove any cognitive component. The exercises were as follows.

1. Five simple interrupted sutures using 2-0 Surgidac on a V-30 needle (USSC); four instrument-thrown ties for each.
2. Five vertical mattress sutures using 2-0 Surgidac on a V-30 needle (USSC); four instrument thrown ties for each.
3. Figure-of-eight suture using 2-0 Surgidac on a V-30 needle (USSC), performed "at depth" in an Annexe Art jig, with four hand-thrown knots. The entry and exit points were 1 cm apart at the four corners of a square.
4. Continuous suture, 8 cm, using 2-0 Polysorb (braided suture) on a GS-24 needle (USSC), performed at surface level or "at depth" in an Annexe Art jig, with a buried suture at the beginning and an Aberdeen sliding knot at completion. The suture points were marked 1 cm either side of the wound and 1 cm apart. The idea behind these markings was that this would obey Jenkins rule and mimic a midline mass closure.

Statistical analysis was undertaken using the Statistical Package for Social Science (SPSS, Chicago, IL, USA). Nonparametric data were analyzed using the Mann-Whitney U-test between groups and the Wilcoxon rank sign when examining within the same group. A probability value of less than 0.05 was deemed significant.

Results

Stage 1

The median times for each exercise were 37.0, 38.0, and 35.5 seconds, respectively; and the median number of movements were 62.5, 69.0, and 81.0 for each exercise. The relation between movements and time were thus 1.71, 1.86, and 2.36; these ratios were all statistically significantly different ($p = 0.002$ for 1 vs. 2; $p < 0.001$ for all others). The correlations for the relation between time and movements were also different for all three: Spearman's ρ was 0.670, 0.757, 0.696 (all $p < 0.001$).

Stage 2

The time taken and the number of movements required to perform the knot-tying and suturing tasks are shown in Tables 1 and 2. The data demonstrate that for most exercises both the time taken and the number of movements required to perform the task can distinguish experienced from nonexperienced surgeons to a significant degree. The ability to discriminate between groups in terms of one repetition of a task versus five repetitions are also significant.

The relation of movements and time for these subjects is calculated and represented in Table 3 (for knot tying) and Table 4 (for suturing), with statistical values shown for these ratios. The second sets of numbers in both tables represent the standardized movements per minute (SMM). These data were calculated by multiplying the movements time ratio by 60, giving the number of movements that would be undertaken if that exercise were to be performed for 1 minute and thus standardize the data for comparison. For knot tying this number is normally in the range of 120 to 140, and for suturing it is 90 to 105 movements per minute.

The effect of rehearsing the tying 4/0 monofilament sutures is shown in Table 5. They were tied at either side of the five repetitions of 2/0 braided suture. The BSTs decreased their movements and the time taken by at least 20%. There is little or no effect on the performance of the HSTs.

Table 1. Median time and number of movements performed while undertaking a number of knot-tying tasks.

Knot-tying task	Time (seconds) BST	HST	p	Movements (no.) BST	HST	p
2/0 Monofilament	19 (16, 22)	14 (11, 18)	0.004	37 (35, 48)	33 (26, 36)	0.006
4/0 Monofilament (4 knots)	21 (16, 28)	16 (12, 17)	0.013	41 (34, 52)	30 (27, 37)	0.029
2/0 Braided × 1	15 (12, 18)	11 (10, 12)	0.003	29 (27, 38)	25 (22, 28)	0.005
2/0 Braided × 5 repeats	70 (62, 86)	57 (51, 63)	0.003	153 (144, 179)	125 (117, 144)	0.003
4/0 Monofilament (4 knots)	15 (14, 21)	13 (11, 15)	0.03	33 (29, 40)	30 (25, 34)	0.163
4/0 Monofilament (10 knots)	34 (32, 48)	26 (24, 29)	< 0.001	80 (72, 101)	57 (52, 68)	< 0.001

BST: basic surgical trainee; HST: higher surgical trainee.
Results are the median, with the first and third interquartile ranges in parentheses (for Tables 1–5).

Table 2. Median time and number of movements performed while undertaking a number of suturing tasks.

Suturing task	Time (seconds) BST	HST	p	Movements (no.) BST	HST	p
Interrupted suture	322.5 (300, 383)	250 (220, 300)	0.012	551 (501, 614)	410 (390, 494)	0.02
Vertical mattress	451 (303, 524)	315 (268, 331)	0.001	719.5 (559, 918)	494 (424, 555)	0.001
Continuous (superficial)	330 (298, 354)	229 (215, 244)	< 0.001	563 (523, 645)	405 (375, 431)	< 0.001
8 cm continuous (deep)	349 (327, 382)	259 (234, 303)	0.001	597 (522, 653)	420 (401, 430)	0.001
Figure-of-eight	84 (77, 112)	56 (42, 62)	0.001	133 (100, 156)	93 (71, 102)	0.003

Table 3. Number of movements/time taken ratio while undertaking a number of knot-tying tasks.

Knot-tying task	Movements/time ratio BST	HST	p	Standardized movements (no./min) BST	HST
2/0 Monofilament	2.1 (2.0, 2.4)	2.2 (2.1, 2.3)	0.253	124 (119, 142)	132 (124, 137)
4/0 Monofilament (4 knots)	2.0 (1.8, 2.3)	2.1 (2.0, 2.4)	0.383	123 (111, 136)	126 (117, 141)
2/0 Braided × 1	2.1 (1.9, 2.4)	2.3 (2.2, 2.5)	0.096	125 (112, 147)	138 (130, 152)
2/0 Braided × 5 repeats	2.2 (1.9, 2.4)	2.23 (2.2, 2.5)	0.318	133 (113, 147)	134 (129, 147)
4/0 Monofilament (4 knots)	2.1 (1.9, 2.3)	2.4 (2.3, 2.4)	0.004	123 (117, 135)	144 (136, 144)
4/0 Monofilament (10 knots)	2.2 (2.0, 2.4)	2.3 (2.1, 2.4)	0.603	130 (121, 145)	137 (126, 147)

Table 4. Number of movements/time taken ratio for a number of suturing tasks.

Suturing task	Movements/time ratio BST	HST	p	Standardized movements (no./min) BST	HST
Interrupted suture	1.7 (1.6, 1.7)	1.7 (1.6, 1.8)	0.868	101 (98, 103)	102 (94, 105)
Vertical mattress	1.7 (1.6, 1.8)	1.7 (1.6, 1.7)	0.088	104 (98, 106)	101 (95, 103)
8 cm continuous (superficial)	1.7 (1.6, 1.9)	1.7 (1.7, 1.8)	0.667	104 (101, 111)	104 (101, 111)
8 cm continuous (deep)	1.7 (1.5, 1.8)	1.6 (1.5, 1.7)	0.240	95 (91, 101)	95 (91, 101)
Figure-of-eight	1.5 (1.4, 1.7)	1.7 (1.5, 1.8)	0.029	87 (83, 99)	103 (89, 110)

Discussion

Previous assessments of dexterity in surgeons have used evaluation methods based on tests used in the general population. Motion analysis permits direct measurement of these specific skills that have been developed through practice. Therefore it is a superior, appropriate measure of surgical dexterity, provided simple assessment of the quality of the task is also undertaken. All subjects were instructed to ensure that the knot or tie was laid correctly and square, and this was confirmed. Because ICSAD relies on standardized tasks, it tests only the quantitative component of dexterity and removes the requirement for the surgeon to exercise the judgment component of the technical performance of suture placement. He or she can then concentrate on pure task dexterity, which makes this assay an ideal tool for assessing dexterity. Thus motion analysis in combination with close supervision of technique and visual inspection of the knot allows a performance to be crucially analyzed on more than one level, deterring those who attempt to perform the task with haste and scant regard to performance. Work in porcine models has shown that a tensile force of 5 N is the minimum holding force required to secure a knot on a vessel in the pelvis [30]; for a knot to slip, it must be incorrectly tied (i.e., incorrectly oriented or not laid flat) [30–32]. Therefore, for correctly tied knots, failure occurs only with breakage.

The same principles apply to suturing with standardization of task performance, with only a simple qualitative measurement (i.e., has the knot been laid correctly?) being required. Separate assessment of qualitative suturing that involves suture placement and

Table 5. Number of movements and time taken to tie four knots at a depth with a 4/0 monofilament suture before and after throwing five repeats of four knots with a braided suture.

	BST			HST		
Parameter	Before	After	*p*	Before	After	*p*
Number of movements	41 (34, 52)	33 (29, 40)	0.017	30 (27, 37)	30 (25, 34)	0.6
Time (seconds)	21 (16, 28)	15 (14, 21)	0.004	16 (12, 17)	13 (11, 15)	0.11

quality of closure is necessary and possible [33]. Qualitative and true quantitative assessments of suturing must be done separately or the assessment fails to exhibit construct validity. This is because an inexperienced surgeon may close a wound with fewer sutures, believing it to be acceptable but artificially generating a shorter time than a more experienced surgeon, who has placed more sutures [34]. The experiments show that the more experienced surgeons perform these tasks in less time making fewer movements. This raises the question: Are they taking less time because they are performing rapid movements to complete the task, or are they making fewer movements to generate the faster time? The answer is achieved by calculating the number of movements per unit time, what we have termed the standardized movements per minute (SMM) (Tables 3, 4). These data suggest, and indeed confirm, the idea that experienced surgeons are more economical with their movements; that is, the experienced surgeon makes fewer moves to complete the same task even though the rate of the movements for experienced and inexperienced surgeons is similar (the SMM).

This relation between time and motion is not fixed, varying according to the exercise being undertaken, whether it is knot tying or suturing with hand- or instrument-thrown knots. This again emphasizes the fact that it is imperative to measure the number of hand movements and the time to give a true reflection of dexterity. The relation between hand movements and time is greater than 1:1, and there is always a significant correlation between the two—an important concept. For simple knot tying the rate is approximately two movements per second (SMM approximately 120) for both junior and senior trainees, and for suturing it is closer to 1.7 movements per second (SMM approximately 100). These figures appear remarkably constant whether knot tying or suturing.

When measuring these task performances, should a single measurement or multiple measurements of the same task be undertaken? What the data show is that a single performance of an exercise can discriminate as strongly as the sum total of five repetitions of the same exercise, suggesting that a single performance of a simple exercise is sufficient for assessment, although multiple exercises could be offered in any form of dexterity assessment.

When junior trainees undertook a knot-tying exercise with 4/0 monofilament, a suture assumed to require more dexterity to tie, their dexterity improved after tying a series of 2/0 braided sutures (i.e., a warm-up). This enhanced performance was in the region of a 20% decrease in time and motion for the BSTs. It suggests that a surgeon, especially an inexperienced one, would benefit from a "warm-up" before undertaking more dextrous tasks or if they were undergoing any form of assessment. Thus with any form of assessment, either a warm-up period must be offered to ensure optimal performance or only certain exercises should be used for the assessment.

Ericsson et al. suggested that expert performance in most areas or skills takes approximately 10 years to achieve. This expert performance is a mixture of technical skills and knowledge. The skills come through daily deliberate practice for up to 4 hours a day [35]. The concept of improving dexterity skills through daily practice was borne out by Kopta [36], who found little improvement in cognitive knowledge over a 4-year residency although there was an increase in psychomotor skill. There is also little support in the psychology literature for a talent-based view of expert performance (for those that believe expert performance is a result of talent, instruction, practice, and genetic factors); this implies that there is little point in attempting aptitude testing prior to a surgical program to identify the best performers. This work, with extensions, provides a basic method for evaluating who has acquired the basic dexterity (through practice and rehearsal) to follow a career in surgery. It would also fit in with the criteria suggested by Gough and Bell [37], providing a feasible objective assessment (technically and economically) appropriate for the trainee. It would allow selection of appropriate individuals who have the drive to become committed surgeons and would avoid the wastage seen in some programs [38]. It would also allow monitoring "key stepping stones" when evaluating trainees [39], although any assessment can be tailored to the requirements of that specialty.

What these experiments do not answer is whether all surgeons reach the same level of dexterity, whether with extended practice they can all reach the same level, or how long it takes to reach these levels of dexterity. Answering these questions would require much longitudinal data collection to measure the change possible during a single session and how many of these sessions are required before that surgeon reaches his or her optimal performance. Further work is needed to examine the relation between the ICSAD score and performance on aptitude tests before we can eliminate or accept that these techniques can predict future surgical dexterity.

Résumé. On a exploré les possibilités d'utiliser l'analyse quantitative des mouvements dans l'évaluation objective de la dextérité chirurgicale simple grâce à l'appareil d'évaluation chirurgicale de l'Imperial College (Imperial College Surgical Assessment Device) (ICSAD). On a analysé la réalisation des nœuds et sutures en chirurgie afin de savoir si on peut distinguer les chirurgiens d'expérience différente. D'après ces résultats, on peut effectivement discriminer significativement entre les chirurgiens juniors et seniors en termes de temps passé et le nombre de mouvements effectués. Le rapport entre le temps nécessaire et le mouvement a été variable, dépendant de l'acte entrepris: suture simple, suture en profondeur, ou réalisation d'un nœud (1.71 vs. 1.86 vs. 2.36, $p = 0.002$ pour 1 vs. 2; $p < 0.001$ pour les autres). Lorsque le nombre de mouvements par minute (Standardised Movements per Minute) a été pris en compte, les tests indiquaient que les deux groupes travaillaient à une allure similaire, dépendant de la tâche, impliquant que plus le chirurgien était expérimenté, plus il accomplissait l'acte avec une économie du geste avec moins de mouvements plutôt qu'avec plus de rapidité. L'analyse des mouvements confirme la validité «apparente» et «calculée» et semble être une évaluation fiable de la dextérité chirurgicale simple. Son utilisation objective pour évaluer la dextérité et la compétence doit être encouragée.

Resumen. Se investiga la posibilidad de aplicar el análisis cuantitativo de movilidad, a la valoración objetiva de la destreza quirúrgica, mediante la aplicación del protocolo del dispositivo de evaluación del Colegio Imperial

de Cirugía (ICSAD) junto con un análisis cualitativo subjetivo. En cirugía de banco se realizaron suturas y nudos con el objetivo de discriminar la destreza entre cirujanos con más o menos experiencia. Los ejercicios discriminaron, de forma significativa, a los cirujanos jóvenes de los más experimentados, tanto por lo que al tiempo empleado se refiere como por lo que al número de movimientos atañe. Se demostró que tanto el tiempo necesario como el número de movimientos necesarios para realizar estos actos varía según el tipo de sutura: sutura simple, sutura profunda y nudo quirúrgico (1.71 vs. 1.87 vs. 2.36, $p = 0.002$ para uno vs. dos; $p < 0.001$ para las demás combinaciones). Al estudiar el número de movimientos por minuto, se comprobó que ambos grupos actúan a una velocidad similar, lo que significa que el cirujano con más experiencia trabaja no a una mayor velocidad sino con menor' número de movimientos. Dadas, la validez del modelo experimental y la autenticidad de los actos evaluados, este proceder constituye un método fiable para la valoración de la destreza quirúrgica. De ahí, que se deba fomentar su utilización en la valoración objetiva de las competencias quirúrgicas.

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