Bimanual dexterity assessment: validation of a revised form of the turning subtest from the Minnesota Dexterity Test

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Bimanual coordination underlies many daily activities. It is tested by various versions of the old Minnesota Dexterity Test (dating back to 1931,'turning' subtest). This, however, is ill standardized, may be time-consuming, and has poor normative data. A timed-revised form of the turning subtest (MTTrf) is presented. Age-related norms and test–retest reliability were computed. Sixty-four healthy individuals, 24–79 years, comprising 34 women, were required to pick up 60 small plastic disks from wells, rotate each disk, and transfer it to the other hand, which must replace it, as quickly as possible. Two trials were requested for each hand (ABBA sequence). The average time (seconds) across the 4 trials gave the test score. Participants were grouped (CART algorithm) into 3 statistically distinct ($P < 0.05$) age × score strata, with cutoff 53+ and 73+ years, and tested at baseline and after 1 week. Test–retest reliability was measured both as consistency [intraclass correlation coefficient (ICCs) model 2.1] and as agreement (Bland–Altman plot). From the ICCs, the individual test–retest minimal real difference (in seconds) was computed. The whole MTTrf took less than 4 min to administer. Baseline scores ranged from 40 to 78 s. The ICCs ranged from 0.45 to 0.81 and the minimal real difference ranged from 6.68 to 13.40 s across the age groups. Fifty-nine out of 64 observations (92%) fell within the confidence limits of the Bland–Altman plot. The MTTrf is a reliable and practical test of bimanual coordination. It may be a useful addition to protocols of manual testing in occupational therapy. *International Journal of Rehabilitation Research* **39:57–62**

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Introduction

A useful operational definition of manual dexterity is ' the ability to make skillful, controlled arm-hand manipulations of larger objects' (Elfant, 1977). This leaves a practical distinction with respect to finer finger manipulation. Many tests are available from the literature [for a review see Yancosek and Howell (2009)]. Most of these explore unimanual dexterity. Bimanual coordination, however, is specifically involved in many daily activities (from buttoning a shirt to typing on a keyboard) and is a specific skill likely to rely on interhemispheric communication through the corpus callosum (Brinkman and Kuypers, 1973) (see the Discussion section). The 'Complete Minnesota Dexterity Test (CMDT)' (Lafayette Instruments, Lafayette, Indiana, USA) is among the oldest tests of manual dexterity. It requires various forms of displacement and turning of wooden or plastic cylinders (3.7 cm wide, 1.8 cm high), to be placed in a series of matched holes (see the Methods section for details). It is the contemporary version of a test dating back to 1931 called the 'Minnesota Rate of Manipulation Test' (MRMT), which subsequently underwent several revisions. The present CMDT and the 1946 version of the MRMT share the same Instruction manual and norms derived (as per the manual instructions) from a sample of 3000 'adult, older, unemployed people of the Depression era', and later for the 1957 version from 11 000 'young people who were employed or seeking employment… the median age was 19 years'. It must be remarked that, despite using the same norms, the CMDT is slightly more difficult than the MRMT (Surrey *et al.*, 2003), presumably because of the smaller size of the holes. The CMDT includes a bimanual subtest [heretofore the Minnesota turning test (MTT)], which is the topic of the present study. This subtest has several flaws. First, it may be time-consuming and perceived as tiring by most patients. In fact (a) the examiner must demonstrate the test in its entirety; (b) the subject is requested to practice by performing the entire test; (c) no time limits are foreseen for each single trial; and (d) no rest time between trials is allowed. Second, the number of trials is decided by the examiner, so that the impact of fatigue and learning remains unstandardized. Third, three procedures may be a source of bias: (a) the visible surfaces of the disks

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to be rotated are red and then black during subsequent trials (unbalanced ABAB sequence); (b) each subsequent trial starts by rotating a disk located on opposite edges of the board (again, an unbalanced sequence); and (c) handedness is not taken into account. Last, the reliability of the available normative data is unacceptable by contemporary research standards. The above flaws may explain why this test is not widely adopted. In the present study a version of the test was realized, after eliminating or at least attenuating the above cited flaws. It was named the 'revised form' Minnesota Turning Test (MTTrf) and administered to adults aged 24–79 years. Hopefully, the MTTrf is more suitable for research and routine clinical assessment. Elderly participants were included because studies adopting different experimental paradigms have shown that bimanual coordination skills decline with age (Bangert *et al.*, 2010; Lin *et al.*, 2014; Shetty *et al.*, 2014). The main goal of the study was estimating two test–retest reliability indexes, one of consistency [the intraclass correlation coefficients (ICCs), model 2.1] and one of agreement (the Bland–Altman plot). From the ICCs the minimal real difference (MRD) (Tesio, 2012) applicable to the study of change in individual participants could be computed. Preliminary normative scores were also provided.

Methods

A convenience sample of 72 healthy adults (students, employees, or retirees) was recruited from the Department of Neurorehabilitation in a teaching Hospital in Milan. We arbitrarily set a target recruitment number of 12 healthy volunteers (six men) for each age decade from 20–29 to 70–79 years. The participants were asked to complete the whole test twice, with a 1-week delay between trials.

Tests and procedures

Before testing, hand dominance was assessed by the Edinburgh Inventory (Oldfield, 1971). The time of day was not necessarily reproduced. The same examiner (a physiatrist) conducted the tests. The MTTrf proposed here is a timed test (faster completion indicates higher 'bimanual dexterity'). The MTTrf utilizes the two parallel black plastic boards of the CMDT, placed on a table in front of the seated individual. Each board is 3 mm thick and has 60 round holes, 3.8 cm in diameter, in four horizontal rows numbered here 1 to 4; 1 is assigned to the row closest to the individual. The examiner sits in front of the participant. The 60 holes are filled by light plastic cylinders (disks) measuring 3.7 cm in diameter and 1.8 cm high, and weighing 15 g each, painted red on one circular side and black elsewhere. Testing begins with the red side facing up. The objective of the MTTrf is to see how fast the participant can pick up, turn, and replace each of the 60 disks, respecting the following procedure.

The first disk to be turned in the first trial is taken from the upper corner of the first row, on the side of the nondominant hand (see Figure 1). For instance, a right-handed patient will have to turn the disk from the upper left-hand corner. The upper surface of the disk will thus change from red to black.

The disk must be picked up and turned with the dominant hand, passed to the other hand, and returned to its original hole. Ideally, a thumb–index pinch should be adopted, but other grasping strategies are allowed in case of hand impairments.

The action is repeated for each adjacent disk along the top row of the board. The next row is started from the side opposite the initial one. The hands reverse their roles (the left hand picks up, and the right hand turns and replaces). The process is repeated for the next two rows.

Adjustments are allowed with the hand used to return the disk to its original hole, to ensure the disks are fully inserted into the holes of the board before the trial is completed. If a disk rolls away from the hole the entire trial is repeated. If the error is repeated then the entire test is considered nonapplicable.

Before testing, the examiner gives verbal instructions and then demonstrates the test until the first two rows (the third and fourth farthest rows, as seen from the subject's side) have been completed, beginning from the initial side assigned to the subject ('mirror' demonstration).

The subject is allowed one complete practice trial. Four further trials (or 'runs') in addition to the practice trial are administered, with 30-s rest periods across trials. Two trials per each beginning hand are requested. Practice and fatigue were balanced through a dominant–nondominant–nondominant–dominant hand first sequence (ABBA design) (Campbell and Stanley, 1963).

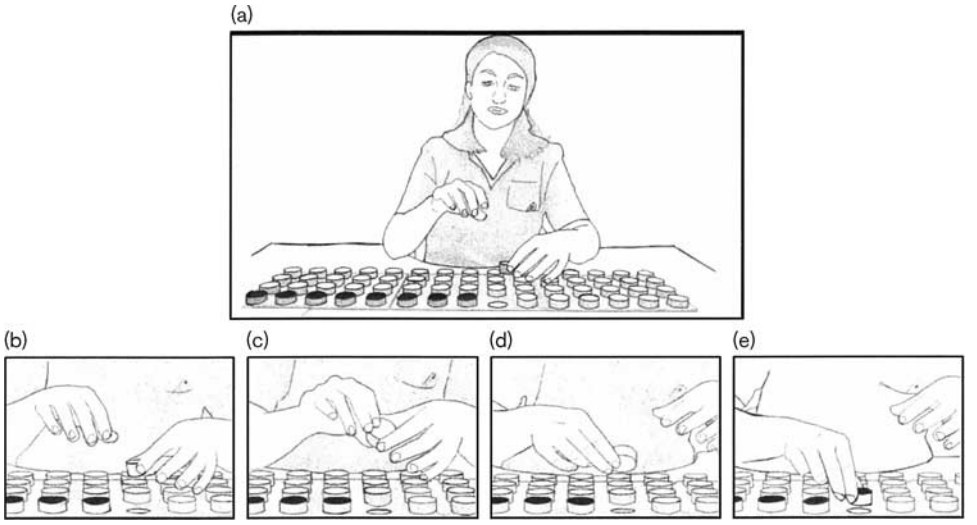
The participant holds his/her picking up hand a few centimeters over the first disk to be lifted. At a 'go' signal, the examiner starts recording the time in seconds taken by the participant to turn all of the 60 disks (black side facing up).

A maximum of 120 s is allowed to complete each test trial. If fewer than 60 disks are turned in one of the two trials, only the number turned and replaced is considered an outcome. This avoids impracticably long tests (mostly recorded in cognitively impaired individuals) while still allowing a within-subject measure of performance.

The mean of the measures (i.e. the number of seconds taken to turn and replace all 60 disks, rounded to the nearest integer) across the four trials represents the test score. The lower the score, the better the outcome.

A sketch of the maneuvers required to turn and replace the disks is given in Fig. 1. A web link to a video of a representative test can be requested to the corresponding author.

Fig. 1



Sketch of the MTTrf (modified from the CMDT battery): (a) general setup; sequence of manipulations; (b) pick-up phase. Initially, the red side of the disk faces upward (here it is white); (c) transfer between hands; (d) turning and (e) replacement; later the black side of the disk faces upward (in the Figure also it is black). CMDT, Complete Minnesota Dexterity Test; MTTrf, timed-revised form of Minnesota turning test.

Statistics

The normality of distributions was assessed using the skewness and kurtosis test (sktest, STATA command). A repeated-measures *t*-test (unequal variances) or the Wilcoxon rank-sum test was used when appropriate for bivariate comparisons.

A statistical keypoint was determining the age limits of groups so as to maximize the between-subjects variance at baseline and minimize the within-subject variance. It is expected that these 'optimal' groups should also show statistically different means. These age limits did not necessarily coincide with the arbitrary decades selected. They were determined using decision-tree modelling, taking into account all possible interactions across MTTrf scores, age, and sex. A classification and regression tree algorithm (CART) (Breiman *et al.*, 1984) was applied. The principles have been summarized elsewhere (D'Alisa *et al.*, 2006). Results were then compared across age groups and time [analysis of variance (ANOVA)].

As long as unimanual dexterity is considered, it is well known that differences may exist between sexes (Endo and Kawahara, 2011; Sartorio *et al.*, 2013; Wang *et al.*, 2015). To the authors' knowledge, data on bimanual tests are missing. For this reason, sex differences in MTTrf scores between baseline and retest were specifically tested (ANOVA).

Reliability was conceptualized and computed according to two approaches. It was given from the perspective of consistency (i.e. the stability of the hierarchy of individual values), and the ICCs model 2.1 were adopted. From the ICCs the MRD (at $P < 0.05$), also referred to as the minimal statistically detectable change, was computed in seconds [see Tesio (2012) for a review of ICCs model selection and correct MRD computation]. Reliability was also given from the standpoint of agreement (i.e. the absolute differences across independent measurements of a stable phenomenon), and the Bland–Altman plot was adopted (Bland and Altman, 1986).

Software

For computation of the optimal age limit across participants, CART software was adopted (CART; Salford Systems, San Diego, California, USA).

All other statistical computations and graphs, including ANOVA and the Bland–Altman plot, were done using the STATA software package (version 13.1 2014; STATA Corp., College Station, Texas, USA).

Ethics

The study was approved by the Ethics Committee of the Istituto Auxologico Italiano, Milan, Italy.

Results

Out of the 72 individuals who were recruited (12 per decade, ranging from 20 to 79 years) eight did not complete the second test, and were excluded from the study. According to CART analysis, at baseline participants were collapsed into three age groups as shown in Table 1: 24–52 ($n = 35$), 53–72 ($n = 20$), and 73–79 years ($n = 9$). It is worth noting that only age led to a partitioning of the sample and that there were no effects of sex or sex × age interaction (not shown). None of the variables allowed us

Table 1 Descriptive summary of numeric results by age

	MTTrf (s)[a] [mean (SD)]			
Age group (years)	Baseline	Retest	ICC (2,1)	MRD (s)
24–52 ($n=35$; 16 M; 4 lh)	45.33 (4.48)	41.81 (3.74)	0.81	6.68
53–72 ($n=20$; 9 M; 0 lh)	53.50 (4.71)	49.40 (4.35)	0.45	10.94
73–79 ($n=9$; 5 M; 1 lh)	64.67 (7.42)	61.89 (6.34)	0.67	13.40

Descriptive summary of numeric results (seconds to turn/replace 60 disks) from the MTTrf given for the three age groups identified through CART analysis. The leftmost column gives the age range, number of participants, number of male participants, and number of left-handed participants across the three CART-determined age groups. The next two columns to the right give the baseline and 1-week retest mean and SD values for MTTrf, respectively. The fourth and fifth columns from left give the intraclass correlation coefficients (model 2,1) and the minimal real difference at 1-week retest, in seconds, at $P<0.05$, respectively.
ICC, intraclass correlation coefficient; lh, left-handed; M, men; MRD, minimal real difference; MTTrf, timed-revised form of Minnesota turning test.
[a]Mean across four trials, two per each beginning hand.

to reject the hypothesis of normal distribution. No single run required more than the 60 s allowed. The grand average (four runs × 64 subjects) (SD) of the time required to complete the MTTrf at baseline was 50.6 (8.42) s. The fastest and the slowest participants at baseline took (average of four runs) 38.5 and 75.5 s, respectively (not shown). Table 1 also shows that there was an evident effect of time (shorter time of test completion at retest). ANOVA across age group, sex, time, and interactions showed significance only for age group and time (both $P=0.000$).

In Table 2 results are contrasted between sexes and time. Again, there was a significant main effect for time ($P=0.016$), whereas neither sex nor sex × time interaction was significant ($P=0.153$ and 0.842, respectively).

Figure 2 gives a graphic representation (box plots) of the MTTrf results recorded at baseline and on retest in the three age groups given in Table 1.

By comparing cells in the second and third column from the left in Table 1 it may be seen at a glance that the average performance declined and their variability increased with age while it improved between baseline and retest.

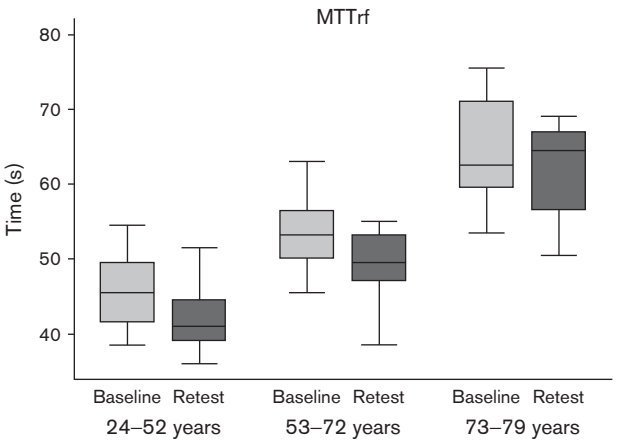
Differences in MTTrf scores were significant ($P<0.05$) both at baseline and at retest across age groups. Within each group, time to completion decreased significantly between baseline and retest (repeated ANOVA, Tukey's post-hoc test, not shown). As a consequence, the

Table 2 Summary of numeric results by sex

	MTTrf (s)[a] [mean (SD)]	
Sex	Baseline	Retest
M ($n=30$, 2 lh)	51.57 (9.12)	48.28 (8.79)
W ($n=34$, 3 lh)	49.75 (7.78)	45.88 (7.53)

lh, left-handed; M, men; MTTrf, timed-revised form of Minnesota turning test; W, women.
[a]Mean across four trials, two per each beginning hand.

Fig. 2



Time in seconds to complete the MTTrf (on the ordinate) at baseline (left box in each pair) and on retest, 1 week apart (right box in each pair), as a function of age group (on the abscissa). For each participant, the completion time is given as the average of four runs, two per each beginning hand (ABBA sequence). Each box spans from the 10th to the 90th percentile of the distribution. The internal horizontal segment gives the median. The upper and lower 'whiskers' are extended to the minimum and the maximum observed values, respectively. See Table 1 for mean and SD. MTTrf, revised form of Minnesota turning test.

consistency across baseline and the 1-week retest was moderate. The fourth and fifth columns from the left give the ICCs and the MRD (i.e. the test–retest change in seconds to be considered significant at $P<0.05$), respectively, across the three age groups. The MRD ranged from 7 to 13 s, rounded to the nearest integer – that is, about 16–21% of the baseline values.

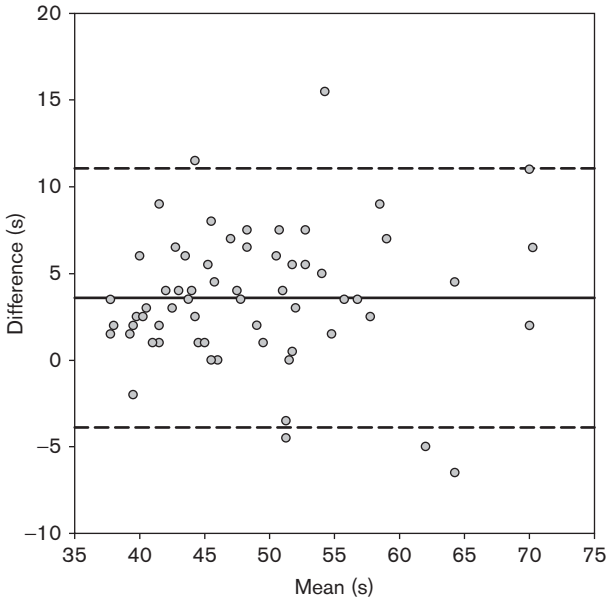
Figure 3 shows the Bland–Altman agreement plot. Baseline–retest differences are given on the ordinate, as a function of the time to completion given in seconds as an average between baseline and retest. The plot refers to data combined from all age groups. It can be seen that five out of 64 values (i.e. 7.8%) were outside the 95% confidence band.

Discussion

The MTTrf performance shows an age-related decrease (i.e. an increase in time to test completion), which was expected. Within each of the three identified age groups, the 1-week test–retest reliability is moderate in terms of both consistency and agreement (ICCs 0.45–0.81; Bland–Altman 95% confidence bands mildly trespassed). This may reflect five major limitations of this study.

First, normative values indicating reliability (including the related MRDs) should be taken cautiously. In fact, the sample size is limited. The main reason was the practical difficulty of recruiting 'healthy' individuals over 69 years of age, while leaving a comparable size across age groups.

Fig. 3



Bland–Altman reliability plot of the MTTrf, performed at baseline and at 1-week retest. The ordinate gives the baseline–retest difference (in seconds). The abscissa provides the average results between the two time points. The intermediate horizontal line marks the average difference, and the upper and lower dashed lines mark the 95% confidence limits. Pitman's test of difference in variance: $r = 0.066$, $n = 64$, $P = 0.602$. MTTrf, revised form of Minnesota turning test.

Second, like in any normative studies the values provided here of course reflect the entire testing procedure adopted. This encompasses the practice trial, the number and the sequence of the trials being averaged, the baseline–retest interval, etc. If these procedures are changed, the generalizability of the normative results can no longer be guaranteed. For instance, if the time taken to complete the MTTrf is computed from only one run as opposed to being averaged across four, the test reliability is likely to be lower, and the MRD higher, than the one provided here. The same holds if the examiner is not the same across time points.

Third, the MRD is expected to change into an unpredictable direction if a longer time interval is considered, because of the fading of the practice effect, on the one hand, and forthcoming biomedical and behavioral changes in the individuals, on the other hand.

Fourth, a practice effect (leading here to a systematic, nonrandom improvement across the two time points) also may obscure the intrinsic test reliability. Test practice is a source of bias. In fact, (a) in clinical trials, any group-average improvement ascribed to treatment (rather than to practice itself) can be overestimated and (b) 'real' individual improvements may be underestimated. The MRD (Table 1), conceived to indicate the threshold for nonrandom individual changes, is likely to be inflated both by the practice effect and, perhaps to a greater extent, by the presumably nonuniform response to practice, enhancing the estimate of within-subject variance.

Fifth, a more general validity limitation relates to the fact that, seen from the perspective of the MTTrf, 'manual dexterity' comes across as a motor performance devoid of emotional meaning and thus unlikely to be exploited in real life. The MTTrf cannot be expected to represent the whole span of complexity of this domain. The conceptual domain of 'manual dexterity' includes person's behaviors ranging from simple finger tapping (Ruff and Parker, 1993) to occupational and artistic gestures, to writing (an item, for instance, of the popular Jebsen-Taylor hand test) (Jebsen *et al.*, 1969) and so on, up to abstract perceptions such as 'manual ability' in daily life (Simone *et al.*, 2011). Also, eye–hand coordination is nested within this form of 'bimanual coordination' and should be considered in interpreting the test results.

Having said that, the proposed MTTrf seems feasible and it seems to provide adequate discrimination across both healthy and impaired individuals in clinical assessments.

First, the practice effect would seem very modest in behavioral tests entailing so few retest sessions. For instance, in a study on 14 parameters of standing balance, the MRD values computed after a 1-week time interval differed by about 10% from those computed after a 3-week interval [see table 4 in Tesio *et al.* (2013)].

Second, the practice-related bias is more a matter of validity than it is of reliability. The 'real' (nonrandom) change due to practice is likely to describe an improved skill bound to the test performed. The improvement does not necessarily generalize to the underlying variable (here, 'bimanual dexterity') the test is assumed to reflect (Tesio, 2014a, 2014b). The mean practice effect can be validly counteracted in research studies with randomized control and treatment groups. However, also in clinical applications in which single individuals are repeatedly tested, the practice effect does not seem a fatal trouble. For instance in this study its concrete relevance remains doubtful. In terms of consistency (ICCs) the effect was found to be significant, despite the small-sized age groups, perhaps because of influential outliers. Yet, absolute agreement as per the Bland–Altman plot across the whole sample remained very close to the limits of statistical acceptability (Fig. 3). In any case, an inflated MRD may decrease the sensitivity to change but increase the specificity of the test: often a welcome protection against false-positive findings.

Third, the biomedical relevance of bimanual testing, however far from perfect, cannot be overemphasized. The ability to make both hands cooperate with complementary gestures develops along with the myelination

of the corpus callosum, and reaches adult levels around the age of 14 (de Boer *et al.*, 2012). Bimanual movements have a distinct neuronal representation that is not amenable to the simple combination of homologous unimanual representations (Mochizuki *et al.*, 2004), and it is widely distributed across both cerebral and cerebellar hemispheres (Swinnen, 2002). Unsurprisingly, bimanual coordination can be primarily affected, even when unimanual movements are not. This is often seen in patients with lesions of the central nervous system (e.g. stroke and Parkinson's disease) (Poisson *et al.*, 2013) in which the basic pathogenic mechanism might be the limited capacity to inhibit forced mirror movements. Another mechanism may be the selective impairment of postural stabilization across body segments, as has been demonstrated, for instance, in cerebellar patients (Bruttini *et al.*, 2015). The need for postural stabilization may critically limit bimanual dexterity, even in healthy individuals, depending on the reciprocal direction of limb movements (i.e. isodirectional or antidirectional coupling) (Esposti *et al.*, 2013).

Fourth, the MTTrf may also be of interest in unilateral impairments (both neurologic and orthopedic) when certain bimanual activities survive through adaptive behaviors. Possibly due to their easier standardization, there has been more research on non-goal-oriented movements in which each hand is required to perform a distinct task (e.g. bilateral in-phase or antiphase tapping or line/circle drawing, rhythmic movements of the hands along nonparallel directions, etc.) (Obhi, 2004). However, most real-life bimanual activities (from buttoning a shirt to opening a jam jar to driving a car) are object and goal oriented and require synchronization of asymmetric hand movements. The task assessed through the MTTrf belongs to this class of movements. Therefore, the test promises some ecological validity.

Last, it may be of interest locating the MTTrf along the continuum of human 'functioning' depicted by the ICF-WHO classification (WHO, 2001). This ranges from organ impairment to activity limitation and participation restriction of the person as a whole. The MTTrf is likely to lie somewhere between the former two benchmarks, thus filling some gaps in the continuum of functional upper limb assessment.

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Conflicts of interest

The authors declare that no conflict of interest exists.

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