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Influence of experience on kinematics of upper limbs during sewing gesture

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ABSTRACT

To teach a skilled motor task, it is crucial to understand the characteristics of expertise. The aim of the present study was to compare the kinematics of the hand sewing task between novices (n = 10), intermediates (n = 10) and experts (n = 10).

Compared to novices and intermediates, the proximal joint of expert participants was less involved in the task than their distal joints. The shoulder of experts stayed closer to the trunk, while the ranges of motion of the wrist and fingers were higher. This ability enabled them to avoid lifting the arm, which was resting on the table. We observed a low cycle-to-cycle variability of the movement pattern for experts, while it was more variable in novices. Moreover, experts shared similar joints synergies attesting of an "experts" common gesture. This knowledge gained about the hand sewing kinematics can be used to refine the training process of dressmakers.

1. Introduction

The hand sewing task requires very high control and regularity of the upper limb. The needle must be inserted up to fifteen times per minutes with a 0.2 mm gap between two threads, up to several hours a day. Even though sewing machines progressively replace manual sewing, hand sewing is still needed in luxury factory for specific designs and clothes.

The seamstress population is declining and is hardly renewed. It raises the issues of task back up and training the new seamstresses, which becomes crucial in several luxury factories. Training is long (typically 3–5 years) and traditionally done on the field by experienced seamstresses. No objective test is available to evaluate the skills, and certification is subjective to an experienced seamstress' judgment. Although biomechanical analysis may provide crucial information about the motor performance during skilled tasks (Uemura et al., 2014), it has not yet been applied to hand sewing.

Hand gestures have been compared between novices and experts in various working fields such as surgery (McNatt et Smith 2001; Lin et al., 2012; Megali et al., 2006) manutention jobs (Plamondon et al., 2014; Min et al., 2012) and music playing (Fernandes et Barros 2012; Parlitz et al., 1998; Jäncke et al., 2000). These studies showed differences in kinematics with experts displaying more stable and reproducible movement (Uemura et al., 2014; Fernandes et Barros 2012; Sakakura et al., 2018). In addition, experts have a specific coordination (Fernandes et Barros 2012) that allow them to avoid unnecessary movement (Zhou et al., 2019; Hofstad et al., 2013; Azari et al., 2020) and to minimize muscle force (Parlitz et al., 1998). In general, experts display a better efficiency owing to an optimization of the energy expenditure and time (Lin et al., 2012; Plamondon et al., 2014; Azari et al., 2020). For Lin et al. (2012), a more efficient movement during laparoscopic surgery is linked to a relative use of joints, specific to expertise: larger range of motion for distal joints compared to proximal joints. Therefore, a kinematic analysis seems relevant to better understand the performance of experts in an upper limb task that requires a high level of accuracy like hand sewing. However, kinematic analysis on the upper limb could be quite complicated considering the numerous degrees of freedom. To simplify this analysis and to better understand the time changes in joint angles, a principal component analysis (PCA) could be relevant (Santello et al., 2002). It provides synergies at the joint level that may be specific to expertise.

The aim of the present study was to compare the kinematics of hand sewing between novices, intermediates, and experts. Our goal is to better understand the characteristics of expertise for this task and to contribute to the task back-up and training. In relation to the state of the art on other upper limb tasks, we hypothesized that experts will produce

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Abbreviations

Add/Abd	Adduction/Abduction
CMC	Coefficient of multiple correlation
DIP	Distal interphalangeal
DoF	Degree of Freedom
Flex/Ext	Flexion/Extension
MCP	Metacarpophalangeal
MSDs	Musculoskeletal disorders
PCA	Principal component analysis
PIP	Proximal interphalangeal
Pron/Sup	Pronation/Supination
SPM	Statistical parametric mapping
TMC	Trapeziometacarpal

specific movement patterns with lower proximal joint ranges of motion and larger distal joint ranges than intermediates and novices.

2. Methods

2.1. Participants

Three groups of participants were studied (total: 30 participants). The first group was composed by ten experts (age: 42.5 ± 14.2 years, height: 1.64 ± 0.08 m, weight: 68.6 ± 13.4 kg, 10 females) with a strong experience in hand sewing (14 ± 10 years, range 3–35 years). They were recruited from two French luxury companies. The amount of weekly practice in hand sewing was about 29.5 ± 5.5 h. The second group was composed by ten intermediate - dressmakers' students (age: 18 ± 2 years, height: 1.62 ± 0.06 m, weight: 54.8 ± 7.5 kg, 10 females) with a small experience (3–6 months). The control group was composed of ten novices with no experience (age: 24.8 ± 3.3 years, height: 1.73 ± 0.08 m, weight: 64.1 ± 10.6 kg, 5 females and 5 males). Participants' skill level was determined by their experience with sewing, we can note that expert group was compose of professional seamstress. Twenty-seven participants were right-handed and three were left-handed (one in each group). None of the participants had an upper-arm injury in the last 6 months. The experiment was approved by local ethics committee of Nantes University (n°20032020-1) and each participant signed an informed consent.

2.2. Experimental task

The experimental session was designed as three set. The sewing cycle was repeated ten times for each set (48 ± 15.8s by set), separated by 1 min of rest. The experimental session, including the anatomical markers disposition lasted about 45 min. The type of stitch sewing used for the experimental task was the "Whip stitch" (Appendix 1). The non-dominant hand presented the tissue (100% cotton tissue) by the index-thumb pinch, the dominant hand holds the needle (no.10) by the index-thumb pinch. The task consisted in a sewing cycle composed by three phases (Fig. 1). First, participants placed the needle against the back of the tissue in the right place to introduce it precisely (Approach phase). Second, participants introduced and pushed the needle through the tissue and grip again the needle (needle-tissue contact phase). The needle-tissue contact phase was determined like the cycle moment when the distance is minimal between markers (LM2 and RM2: placed on the distal head of the 2nd metacarpal) of the left and the right hand, and until the distance between them increase (+3 mm). Third, participants pulled it to stretch the sewing thread (polyester thread no.120) (Pull thread phase). Participants were seated to an adjusted table, in such way that forearms lied on the table, the back was straight, arms were close to the body and elbows were flexed at 90°. Participants were required to sew following a line as close as possible with a gap between each stitch to 2 mm–4 mm. In addition, they were required to sew with fluidity without time constraint. Before each session the thread was cut at 40 cm. Sewing cycle started and finished when the dominant hand was at the highest position (the end of the pull thread phase).

2.3. Kinematics

During each of the three sets, kinematic data were recorded at 100 Hz with a system composed of twelves motion capture cameras (Flex 13, Optitrack, Corvallis, Oregon, USA) placed around the participant, six were focus on fingers area (40 × 40 × 40 cm), others recorded body movement in general. Fifty-two spherical reflecting markers (4 mm in diameter) were placed on anatomical landmarks of upper-limb (Fig. 2) (Wu et al., 2005; Goislard de Monsabert et al., 2012). Marker locations are described in supplemental data (Appendix 2).

We recorded kinematic data for 21 joints with a total of 36 degrees of freedom (DoF). Three-dimensional position of the chest, arms, forearms, hands and the first, second and third fingers for dominant hand and only the first and second fingers for non-dominant hand were considered

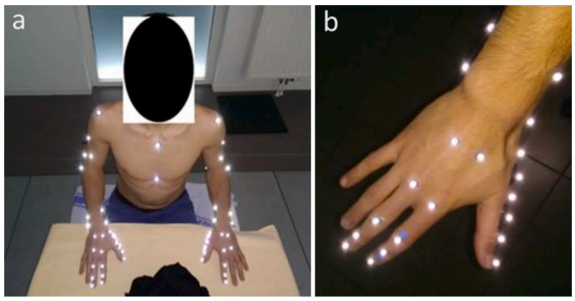


Fig. 2. A. Location of the 52 markers (the marker of the cervical n°7 is not visible). b. Location of the 24 markers of the right hand (dominant). The third finger of the non-dominant hand (left) is not equipped.

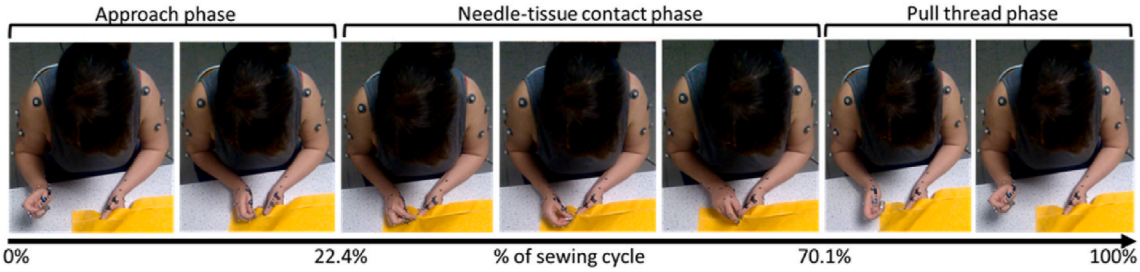


Fig. 1. Photos of sewing cycle phases. Approach phase: participants placed the needle against the back of the tissue in the right place to introduce it precisely. Needle-tissue contact phase: participants introduced and pushed the needle through the tissue and grip again the needle (to 22.4%–70.1% of the cycle). Pull thread phase: participants pulled it to stretch the sewing thread.

during the movement using the kinematic model (Wu et al., 2005; Goislard de Monsabert et al., 2012; Fohanno et al., 2013). Each bony segment was located by three markers and a local coordinate system was created (Fig. 3). The longitudinal axis linked two joint centers oriented proximally (Y for upper-limb, X for the hand). A plan was created with the third marker of the segment, placed on the flexion/extension (Flex/Ext) axis of joint. The Frontal axis (Adduction/Abduction; Add/-Abd) was created perpendicular to the plan oriented frontally (X for upper-limb, Y for the hand). Finally, the transversal axis (Flex/Ext, Z) was orthogonal to both X and Y axes, pointing right (right/radial or ulnar/left hands). Since only Flex/Ext around transversal axis was evaluated for fingers, only two markers were placed on finger phalanges. Two additional markers were placed on the thumb to compute internal and external rotation (X axis) (Cooney et al., 1981). Joint angles were calculated as the product from orientation matrix of proximal segment regarding the distal segment (Cappozzo et al., 2005), and owing to Euler's angles according to rotation sequence: Z (Flex/Ext), X (Add/-Abd), Y (Pronation/Supination; Pron/Sup) around fixed axis. Joint angles obtained during static capture in reference anatomical position, considered like zero angle, were subtracted from angles computed during movement. All calculations were performed using custom-made Matlab scripts (2019b, Mathworks Inc, USA).

The limb that holds the tissue was almost static. We focused on the dominant hand and arm of the participants to analyze 20 DoF on 12 joints. Only the best set of ten cycles, the more regular without parasite movement, were kept then averaged to provide a representative cycle. The three phases were interpolated on 100 points for each participant, then the entire cycle was time normalized from 0 to 100% of the cycle.

2.4. Data reduction

The principal component analysis (PCA) method was used to reduce the DoFs redundancy and identify motor synergies, which describes the covariation of joints' motion during the task (Lambert-Shirzad et Van der Loos 2017). PCA consists of an orthogonal transformation that converts the variables into new uncorrelated principal components, which explain the majority of variation in the data (Deluzio et Astephen 2007). The principal components are arranged in order of their decreasing sample variance. For each principal component, the PCA results provide a coefficient and associated load vectors: the coefficient represents the temporal pattern of the principal component, whereas the load vectors represent the weights of each variable within this component.

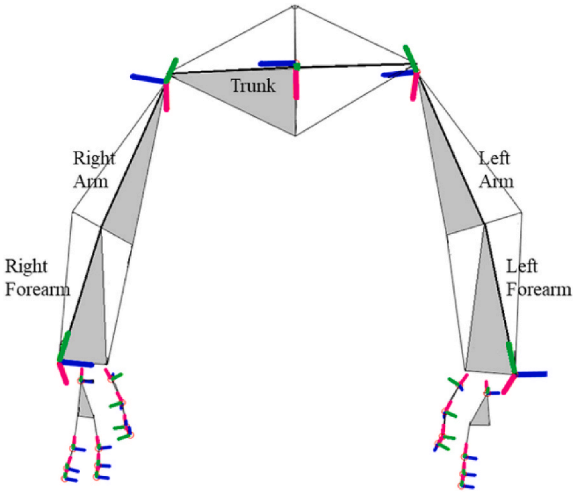


Fig. 3. Position and orientation of the segment coordinate system of upper limbs and trunk. Blue axis is for flexion (Z), green is the rotation axis for upper-limb and adduction axis for hand (X), and red is the adduction axis for upper-limb and the axis rotation for hand (Y). In grey the frontal plan from landmarks.

For each participant, we mean-centered the kinematic data of the ten sewing cycles for each of the 20 DoF. Last, we applied eigenvalue decomposition of the covariance matrix. We considered the principal components needed to explain 90% of the variance of the original dataset (Jackson 2005).

2.5. Statistical analysis

To analyze differences in sewing cycle duration (s) and relative needle-tissue contact phase duration (s) between groups, two two-way ANOVAs with post-hoc (Bonferroni) were performed. (within subject factor = start and end of the needle-tissue contact phase; between-subject factor = Group).

The method of statistical parametric mapping (SPM, Pataky et al., 2015) was used to assess differences in joint angles between the groups through the movement cycle. Specifically, to locate the differences of joint angles across the three groups, we used a one-dimension SPM ANOVA with post-hoc (Bonferroni) for each DoF.

To test the between-group difference in range of motion, a separate one-way ANOVA with post-hoc (Bonferroni) was performed for each DoF.

Coefficient of multiple correlation (CMC, Ferrari et al., 2010) was calculated to assess the variability of the time-varying joint angle profiles across participants (between-subject variability) and across cycles (within-subject variability) for each DoF. Then, to compare CMC between groups, a one-way ANOVA with post-hoc (Bonferroni) was performed for each DoF.

Finally, to compare the number of principal components that accounted for 90% of variance between groups, a one-way ANOVA with post-hoc (Bonferroni) was performed. To compare the load vectors of each principal components between the three groups, one two-way ANOVA with post-hoc (Bonferroni) was carried out (within subject factor = twenty principal components; between-subject factor = Group). To evaluate the similarity of the component's coefficient between participants of a group, a CMC was calculated for the three principal components. To evaluate the correlation of vector load between participants of a group, a Pearson correlation was performed for the first principal component. Then, to compare principal component's vectors loads correlation between groups, a one-way ANOVA with post-hoc (Bonferroni) was carried out.

Statistical analysis was carried out with Matlab (2019b) and Statistica (v10, StatSoft, France). The significance threshold was set at $p = 0.05$.

3. Results

There was a main effect of group ($p = 0.001$) on the duration of the sewing cycle, with the cycle being shorter for experts (3.4 ± 0.8s) than for both intermediates (5.6 ± 1.6s; $p < 0.003$) and novices (5.5 ± 2.2s; $p < 0.005$). There was no difference between intermediates and novices ($p = 1$). The needle-tissue contact phase (second phase) lasted to 0.83 ± 0.08s (25.5 ± 4.5%) to 2.40 ± 0.62s (71.2 ± 4.4%) for experts, to 1.23 ± 0.44s (21.6 ± 2.7%) to 3.97 ± 1.25s (70.9 ± 5.8%) for intermediates, to 1.03 ± 0.16s (20.0 ± 5.8%) to 3.77 ± 0.86s (68.3 ± 3.6%) for novices, of the total cycle. There was no difference between groups.

The SPM analysis revealed significant differences between groups for five DoF (Fig. 4). Specifically, the mean shoulder abduction joint angle was smaller for experts (16.0 ± 0.4°) than novices (36.4 ± 2.1°; $p < 0.006$) over the entire cycle (1–100%), but no differences with intermediates (22.2 ± 1.5°) was observed. Middle-MCP extension was higher in experts than both novices between 11% and 83% of the cycle ($p < 0.001$) and intermediates between 22% and 45% ($p < 0.001$). First-MCP extension was higher for experts than novices between 1% and 16% and between 89% and 100% of the cycle ($p < 0.03$). No differences between intermediates and either experts or novices were observed.

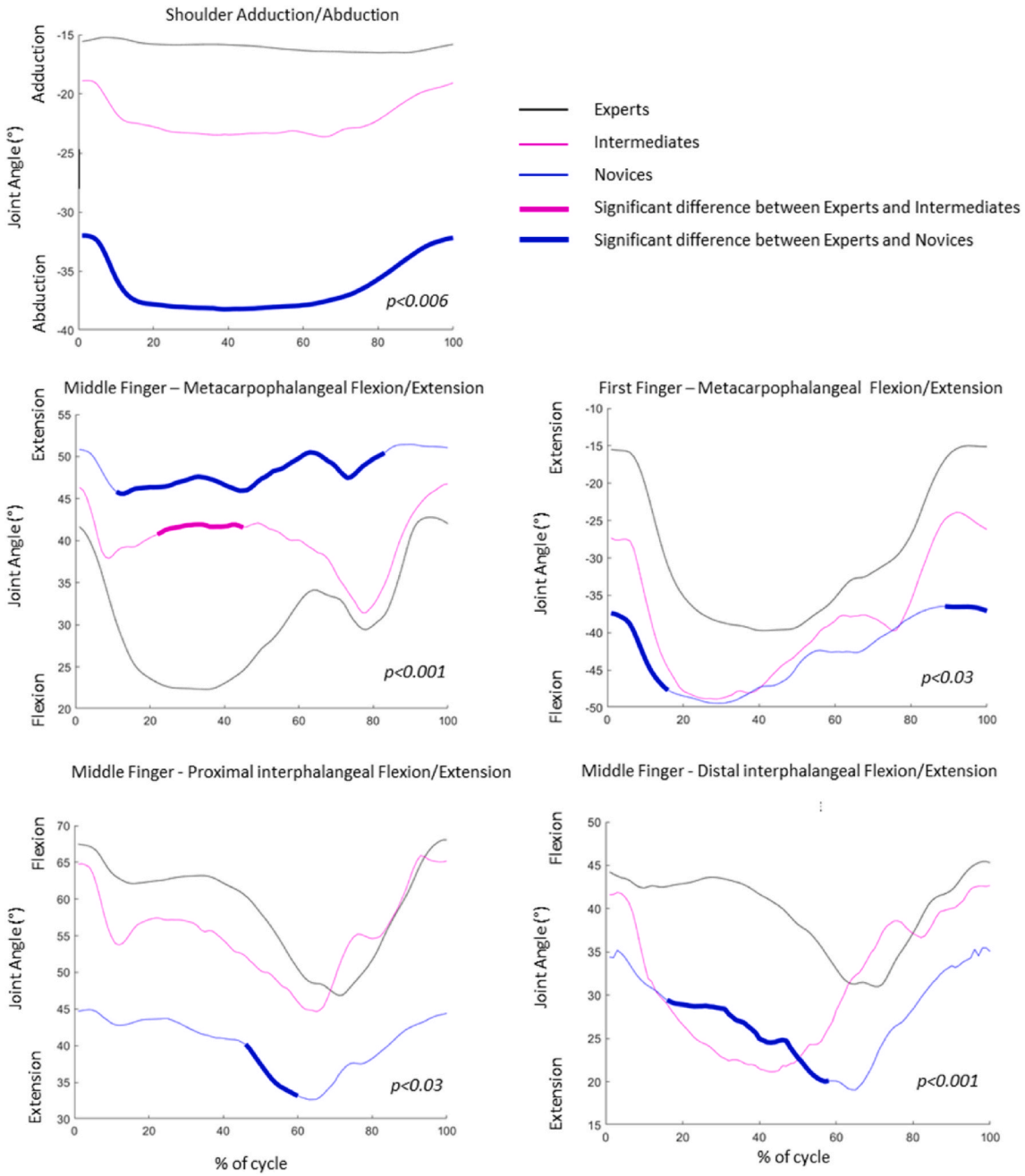


Fig. 4. Time-varying joint angle for the five Degree of Freedom (DoF), which exhibited a significant difference between groups during the sewing cycle. Statistics were performed using the Statistical parametric mapping approach.

Middle-PIP flexion was higher for experts than novices from 44% to 60% of the cycle ($p < 0.03$), no differences between intermediates and either experts or novices were observed. Middle-DIP flexion was higher for experts than novices from 16% to 58% of the cycle ($p < 0.001$), no differences between intermediates and either experts or novices were observed.

The range of motion of the 20 DoF are depicted for each group in Table 1. For the sake of clarity, only the main effect of group is depicted in the table, while the results of the post hoc tests are depicted in the main text. The range of motion of Shoulder-Flex/Ext was approximately 49% smaller for experts than novices ($p = 0.048$). The range of motion was larger in experts than novices for three others DoF: Middle-MCP-Flex/Ext (+84%; $p = 0.006$), Wirst-Add/Abd (+97%; $p = 0.002$) and Wrist-Pron/Sup (+49%; $p = 0.034$). The range of motion was larger in intermediates than novices for two DoF: Wirst-Add/Abd (+88%; $p = 0.003$) and First-MCP-Flex/Ext (+47%; $p = 0.045$) (Table 1).

The CMC analysis revealed that some experts' DoFs motion were similar between individuals. For 6 DoF we found CMC values > 0.4, revealing a low between-subject variability: Wrist-Pron/Sup (0.41), Wirst-Add/Abd (0.60) (Fig. 5), First-MCP-Add/Abd (0.44), First-MCP-Flex/Ext (0.43), First-PIP-Flex/Ext (0.50) and First-DIP-Flex/Ext (0.43). For intermediates we found 3 DoF with a CMC over 0.4: First-PIP-Flex/Ext (0.56), First-MCP-Flex/Ext (0.45) and Thumb-TMC-Add/Abd (0.43). None of the CMC values were above 0.4 for novices, revealing a large between-subject variability for all the DoF.

The between-subject variability of the time-varying joint angle profiles was different between groups (main effect $p = 0.02$). Specifically, a lower variability was found in the expert group (CMC 0.65 ± 0.14) compared to the novice group (CMC 0.49 ± 0.13; $p < 0.02$). No significant difference was observed between intermediates (CMC 0.52 ± 0.10)

Table 1
Joint ranges of motion of 20 DoF Labels (abbreviations Appendix 3).

DoF Labels	Experts Range of motion (°)		Intermediates Rangeof motion (°)		Novices Range of motion (°)		Main effect of Group
Shoulder-Add/Abd	3.7	±1.7	6.2	±6.2	3.3	±7.0	ns
Shoulder-Flex/Ext	6.2	±4.3 *	8.1	±3.8	12.6	±7.8 *	0.049
Shoulder-Pron/Sup	18.8	±8.8	23.3	±23.8	19.2	±8.9	ns
Elbow-Flex/Ext	20.6	±13.4	18.2	±10.6	14.5	±7.3	ns
Wirst-Add/Abd	13.4	±4.8 *	12.8	±3.8 #	6.8	±2.4 *#	0.001
Wirst-Flex/Ext	20.4	±8.7	20.5	±8.3	17.3	±8.9	ns
Wrist-Pron/Sup	59.8	±20.7 *	52.4	±16.9	40.0	±14.5 *	0.037
First-MCPAdd/Abd	14.7	±4.5	13.9	±5.7	9.9	±4.4	ns
First-MCP-Flex/Ext	28.1	±8.5	30.9	±14.0 #	18.1	±8.4 #	0.024
First-PIP-Flex/Ext	26.7	±6.9	32.1	±8.6	18.8	±7.8	ns
First-DIP-Flex/Ext	20.4	±5.5	23.3	±6.6	19.5	±9.3	ns
Middle-MCP-Add/Abd	7.0	±2	6.9	±1.3	6.3	±2.9	ns
Middle-MCP-Flex/Ext	25.8	±5.1 *	20.6	±9.5	14.0	±4.7 *	0.006
Middle-PIP-Flex/Ext	26.8	±7.8	26.8	±9.7	19.0	±9.1	ns
Middle-DIP-Flex/Ext	23.5	±7.7	35.0	±17.1	22.8	±10.9	ns
Thumb-TMC-Add/Abd	10.4	±3.9	12.8	±4.4	7.3	±2.7	ns
Thumb-TMC-Flex/Ext	13.0	±6.4	10.7	±6.2	9.5	±5.1	ns
Thumb-MCP-Add/Abd	9.1	±3.9	9.9	±3.1	7.4	±3.1	ns
Thumb-MCP-Flex/Ext	13.1	±4.1	17.2	±5.9	12.7	±6.3	ns
Thumb-IP-Flex/Ext	19.2	±6.3	21.5	±5.8	17.6	±7.7	ns

Joint ranges of motion (°) of 20 DoF Labels for groups of experts (n = 10), intermediates (n = 10) and novices (n = 10). Significant difference between experts and novices (*), between intermediates and novices (#), between experts and intermediates (†). Adduction/Abduction (Add/Abd), Distal interphalangeal (DIP), Flexion/Extension (Flex/Ext), Metacarpophalangeal (MCP), Pronation/Supination (Pron/Sup), Proximal interphalangeal (PIP), Trapeziometacarpal (TMC).

and either experts ($p = 0.07$) or novices ($p = 1$).

For principal components analysis, there was a main effect of group on the number of components needed to reach 90% of the variance accounted force ($p = 0.007$). Specifically, less components were needed for experts (4.3 ± 1.15) than intermediates 5.8 ± 1.03 ($p = 0.013$) and novices 5.7 ± 1.06 ($p = 0.022$) (Fig. 6). No differences were found when we compared the vectors loads between groups for each component ($p = 0.449$).

Regardless of group, the first synergy explained a large part of the accounted variance: $58.9 \pm 11.2\%$ for experts, $51.9 \pm 13.9\%$ for intermediates, and $45.4 \pm 8.3\%$ for novices. We calculated the CMC value for the coefficient of the three first synergies to assess their variability between participants. CMC values reveal a low between-subject variability for the first synergy: experts (0.93), intermediates (0.88), and novices (0.70). CMC values for experts' coefficients of the three first principal components were high, while the CMC values for intermediates and novices was just high only for the two first principal components and lower than experts score (Table 2.).

Pearson's correlation for vector load of the first synergy was higher between experts 0.76 ± 0.06, than intermediates 0.55 ± 0.15 ($p < 0.05$) and novices 0.18 ± 0.27 ($p < 0.001$). The intermediates score was also higher than novices ($p < 0.001$) (Fig. 7).

4. Discussion

Using a kinematic analysis of 21 upper-limbs joints, we observed significant differences in task kinematics between experts, intermediates and novices during a hand sewing task. In accordance with our hypothesis, expert seamstresses exhibited lower proximal joint range of motion and larger distal joint range of motion compared to intermediates and novices. Experts used their shoulder "Shoulder-Add/Abd & Flex/Ext" less and their arm stayed closer to the trunk. Conversely, they used more of their wrist "Wirst-Add/Abd & Pron/Sup" and fingers "Middle-MCP- Flex/Ext". In addition, expert seamstresses took less time to complete the task and exhibited a lower cycle-to-cycle variability than novices.

The reduced task duration found in the present study clearly demonstrates the better performance of experts. It is in accordance with the literature which focused on skilled motor tasks such as surgery (Hofstad et al., 2013; De Laveaga et al., 2012; Azari et al., 2020). Azari et al. (2020) showed that the reduction of task duration is obtained by "reducing extraneous movements" and is often associated with an economy of energy. Lin et al., (2012), indicated that experts' efficiency is associated with a specific relative use of joints and showed a larger range of motion for distal than proximal joint. Finger dexterity, defined as the ability to accurately and rapidly control and coordinate finger movements (Carment et al., 2018), is preponderant for accurate hand tasks. In the present study, we observed that experts used their fingers differently than intermediates and novices. Specifically, during the phase of the needle-tissue contact phase, the middle-finger joints displayed a dramatically higher range of motion in Flex/Ext (+84% for Middle-MCP-Flex/Ext for experts compared to novices). Our results also highlight the important role of the wrist, showing a greater range of motion for the Pron/Sup and Add/Abd for experts. The action of the wrist allows experts to appropriately orient the hand for an optimized fingers action, like place and manipulate the needle. Middle-finger and wrist, with their combined range of motion, are used to push the needle through the tissue, then to pull the thread efficiently during the Pull thread phase, without additional movement of elbow and shoulder. This ability, shared sometimes with intermediates, to favor middle-finger and wrist action rather than shoulder abduction or flexion avoid lifting the arm mass, which stayed close to the body. This could contribute to reduced energy cost and muscle work.

Previous studies showed that experts such as pianists exhibit better regularity and reproducibility during a common precision hand task, as well as greater finger coordination (Fernandes et Barros 2012). The better control of movements was associated with a reduced muscle activation (Jäncke et al., 2000). In our case, a lower cycle-to-cycle variability of the movement pattern was observed for experts compared to novices. In addition, the principal component analysis showed that experts movement required 4.3 ± 1.1 synergies to explain 90% of variance while intermediates and novices required 5.8 ± 1.03 and 5.7 ± 1.06 synergies. This lower number of synergies in experts can be interpreted as a higher dimensionality reduction of the control of the large number of upper limb degrees of freedom (Schieber et Santello 2004). This ability, acquired with long-term practice and sensorimotor feedback (Sobinov et Bensmaia 2021), leads to the initial complex joint coordination to simpler, repeatable, and efficient movement.

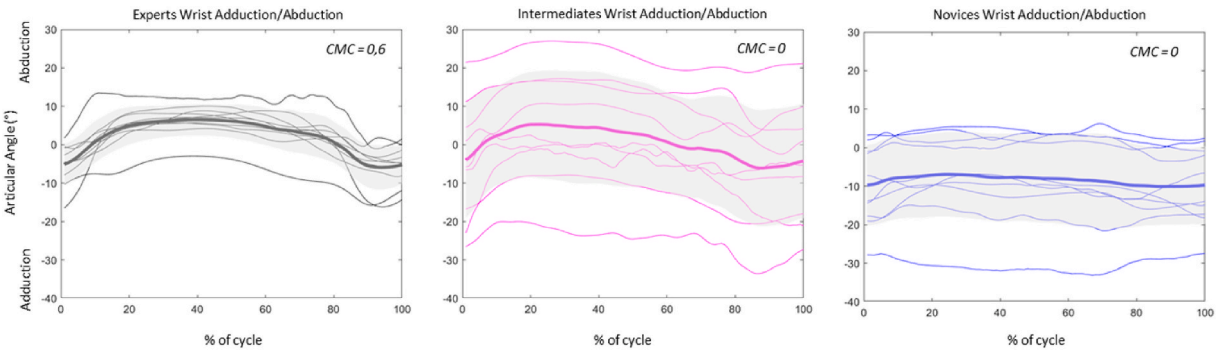


Fig. 5. Individual wrist Adduction/Abduction motion during the sewing cycle in the three groups. Data are depicted for each participant (thin line) and the average for each population (thick lines). The grey area corresponds to the standard deviation across participants. The coefficient of multiple correlation was 0.6 (CMC) for experts and 0 for both intermediates and novices.

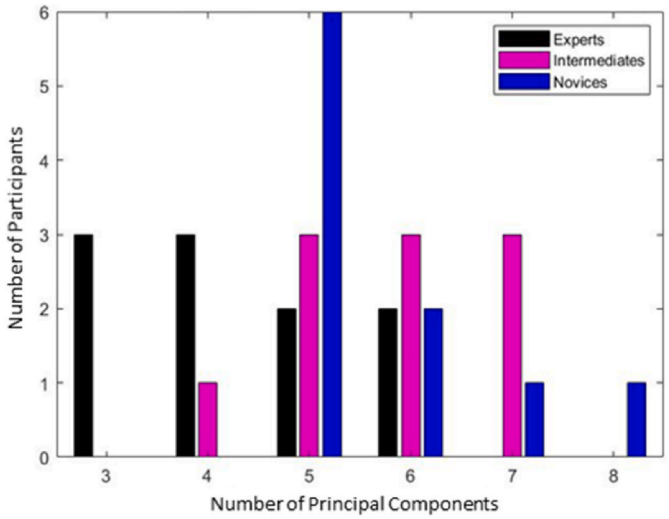


Fig. 6. Number of components needed to explain 90% of the accounted variance.

Table 2
Coefficient of multiple correlation for principal components coefficients within groups.

	PC1	PC2	PC3
Experts	0.93	0.75	0.52
Intermediates	0.88	0.50	NA
Novices	0.70	0.51	NA

Principal Component (PC).

For many authors (Nelson, 1983; Yao et Billard 2019), a skilled movement satisfies conditions such as "economy of effort" or "efficiency", and these characteristics rely on an optimal joint movement pattern. In our case as we have shown, an expert seamstress uses less of their proximal joints (Shoulder-Add/Abd & Flex/Ext) and more their distal joints (Wirst-Add/Abd & Pron/Sup; Middle-MCP-Flex/Ext) as compared to novices, characteristics probably linked to an "efficiency" of movement. Experts shared some joint movements patterns like Wirst-Add/Abd and Wirst-Pron/Sup, or First-fingers joints DoFs (0,4< CMC <0,6). Moreover, as shown by the principal component analysis, the three first synergies are very similar between experts, attesting to an "efficient" common gesture. Fig. 8 describes these most relevant differences between groups that seem to determine the hand sewing performance and could be a target to the task learning. It probably corresponds to an optimal movement for this given task and could be used as training basis for the novice and intermediate seamstress. As suggested by Azari et al., (2020), we could consider that novices learn to complete the task, intermediates learn to move faster, and experts learn to conserve energy by reducing extraneous movements (shoulder use). With training, the movement is optimized and results in better motor control and coordination.

Expert participants were able to avoid lifting their arm, which was resting on the table. In addition, the shoulder range of motion was lower for the experts' group. This behavior is probably crucial to limit the fatigue induced by the task. Thus, it is also probably important to perform the task in that way to prevent MSDs. However, experts bend and twist their wrist further and faster than novices. It can lead to high loads repeated several times during the working days and can expose workers to risk of MSDs like carpal tunnel syndrome (Palmer et al., 2007). In addition to the wrist motion, a precision (pinch) grip is required. According to Finneran et O'Sullivan (2013), forceful gripping, precision tasks and deviated wrist postures are a combination of factors leading to MSDs. Taken all together, these factors may lead to carpal tunnel syndrome (Abbas et al., 2001; Palmer et al., 2007; Dianat 2016). However, it seems important to observe that the tension to insert the needle through the tissue was low. It would be different with another materials like leather. In the present study, it was not possible to isolate risk factors among the experts' participants. For that purpose, the protocol and the method used could be used in a future prospective study to investigate links between the kinematic of the task and the occurrence of MSDs.

The type of stitch sewing used for the experimental task was the "Whip stitch" (Appendix 1). Even though it is rarely used in the professional context, it is easier to perform, which was an important aspect to make comparison between groups. Moreover, it is representative of many types of stitch sewing allowing to generalize our results for others type of hand stitch sewing. Nevertheless, the particularity of the luxury hand sewing is the accuracy of the task and the quality of the tissue, which is generally thin. This context induces specific characteristics of expertise that are evaluated in the present study. However, if different materials such as leather are used, tools and applied forces would probably be different. The decisive factors of task skill would change, causing probably different characteristics of expertise and different joint relative use. To respond to higher forces, the weak joints of fingers would be less used, the type of grasp may change to be 'power grasp' involving the third and little fingers (Cutkosky 1989) and the wrist would be stabilized and used like force transducer (Finneran et O'Sullivan 2013). Nevertheless, we think that some characteristics of expertise would still be present for harder materials: fewer variable cycles (Sakakura et al., 2018), faster movement or reducing unnecessary movements (Plamondon et al., 2014) leading to simpler movement in respect to a PCA analysis. Therefore, while we speculate that our results would be generalizable to the tasks of seamstress, it could be very

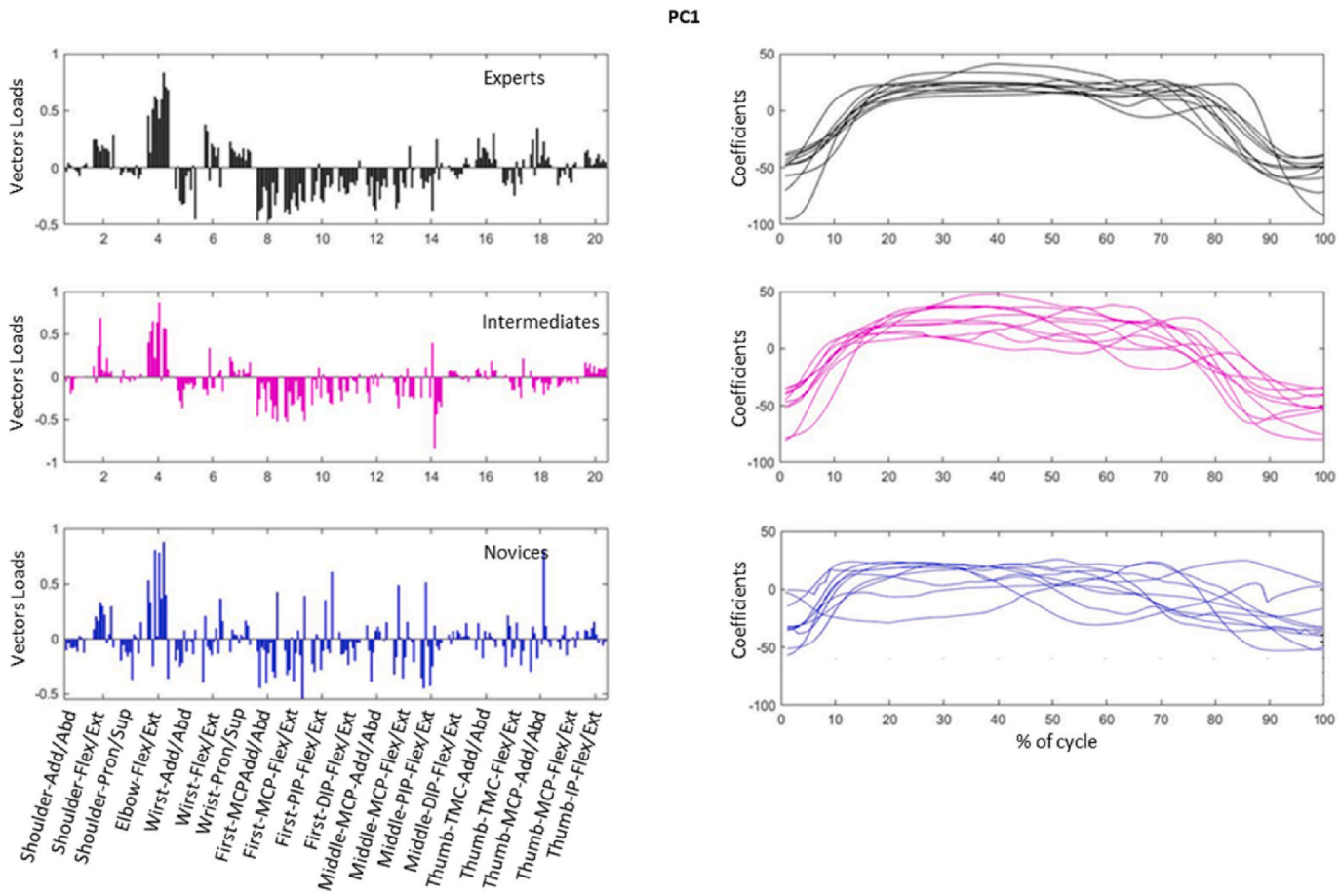


Fig. 7. Vectors loads (left column) and coefficients (right column) of the first principal component for each group: experts (black), intermediates (magenta) and novices (blue).

relevant to duplicate the present study to better understand how they could adapt their gesture to harder materials.

This study requires consideration of some limitations. On the one hand regarding our research design. First, the expertise level was evaluated by the level of experience. We use no other tools to subjectively evaluate the level of expertise. Nevertheless, in our case the level of expertise were sufficiently links to the experience to correctly differentiate the participants in three separated groups. Second, the level of precision was not evaluated during the experimental task. Participants had to follow a line as close as possible with a gap between each stitch to 2 mm–4 mm, the instruction was the same for each group. The precision was not straightforward to assess and, to our knowledge, there is no way to measure it. Third, the needle was held only with the dominant hand and only 3 over 30 participants were left-handed. Therefore, the applicability of our results to left-handed could be debated. Even if we know that right-handers showed a significant asymmetry of topological cortical network properties to privilege right hand movement (Andersen et Siebner 2018), their cortical surface area of regions related to manual motor control is similar to left-handers (Andersen et Siebner 2018) and their dominant manual dexterity induced is not necessarily different. Then, our results could be extended for left-handed participants, and we do not think that the participation of left-handed in our experimental design influence our results. However, our findings are not generalizable to both dominant and non-dominant hand due to the dexterity difference between both hand (Walker et Henneberg 2007).

On the other hand, we must consider some limitations regarding the measuring device. First, despite twelves cameras placed around the participant (among 6 focused on fingers), markers placed on fingers were sometimes hidden by the tissue or the hands. When this occurred, we rebuilt the makers trajectory with a “rigid body rebuilding”. While this event occurred during almost all acquisitions, it was on very short time (<10 frames). Therefore, considering the good accuracy of the rigid body rebuilding method (Biryukova et al., 2000), we are confident that this issue did not influence our results. Second, markers were placed on an anatomical landmark. Thus, skin movement can lead to a displacement of markers during movement (radio-ulnar movement) and sometimes do not exactly represent the reality, and this is a common limit for kinematic analysis (Ryu et al., 2006; Laitenberger et al., 2015). However, it likely occurred in all the participants making the comparison between population meaningful. We therefore believe that it did not affect the main conclusions of our study. Third, more generally, the kinematic methods for the whole upper limb and hand were developed and validated in previous studies Laitenberger et al., (2015); (Fohanno et al., 2014; Goislard de Monsabert et al., 2012). This method has already been used for several other applications like paddling (Fohanno et al., 2014). While we acknowledge the classical limitations of our kinematic model (i.e., estimation of joint center locations) (Begon et Lacouture 2005), we think that the hand sewing task is particularly adapted to the use of this model that enabled us to make appropriate comparisons between groups. Within the model used, the thumb is probably the most complicated segment, there is a lack of consensus in the literature for the model of the thumb to be used. We used the method of Cooney et al., (1981) to analyzed trapezoid metacarpal joint movement. Although it was considered as valid for Flex/Ext and Add/Abd, it may contains inaccuracy for rotation (Domalain 2010). It may have influenced our results and this degree of freedom should be interpreted with more caution.

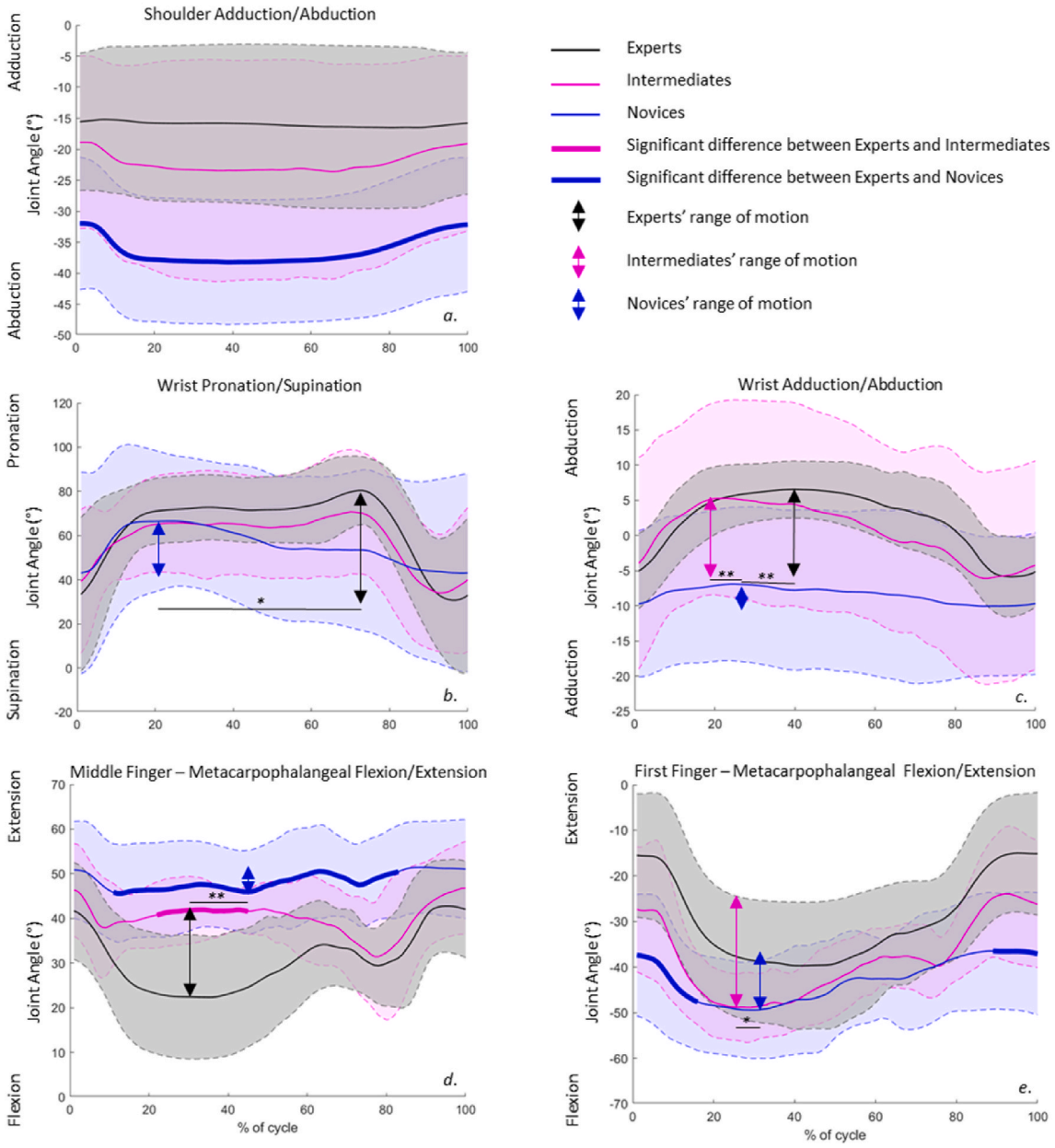


Fig. 8. "Corridors" of movement, which seem to be essential for expert movement. They are compared to intermediate and novice movements. The line represents mean movement, dashed lines represent standard deviations of movement for each group. Significant differences are represented by thick line for joint movement (Statistical parametric mapping) and by asterisk for range of motion (*$p < 0.5$; **$p < 0.1$).

5. Conclusion

The study was designed to provide better understanding of hand sewing to improve the task back-up and training. Our kinematic analysis showed the importance of posture and relative use of joints. Thus, it seems crucial to keep the arm close to the body and use more wrist and fingers joints rather than the shoulder and elbow. Efficient and fast joint movement shared by expert seamstresses were highlighted (Fig. 8) and can be used as learning targets to improve stitch sewing performance. Future studies would analyze the neural control associated to the kinematic that is used by experts to obtain the specific coordination and finger dexterity highlighted in the present study. In addition, the method developed would be used in a prospective study to isolate risk factors of MSDs.

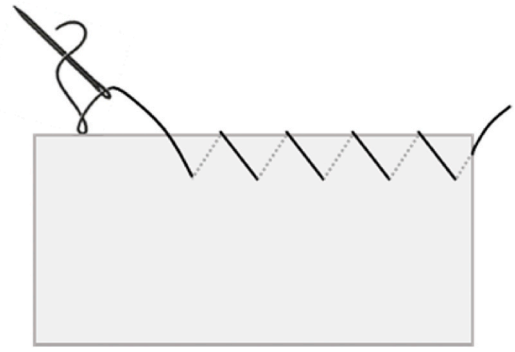
Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix.1. : Type of stitch sewing used for the experimental task: the "Whip stitch"



Appendix.2. : Markers dispositions

"C7" was placed on cervical n°7, "ST" on the highest part of sternum and "STX" on xiphoid process.

For right side (dominant): "RSH" was placed on lateral part of acromion. "RU1","RU2", "RU3" was a cluster of markers placed on the lateral face of the arm. "REM" and "REL" was placed on medial and lateral elbow epicondyle respectively. "RU" and "RR" was placed on the extern face of ulnar and radius 5 cm proximally from the wrist and "RWU" and "RWR" on ulnar and radius distal head respectively.

For right Hand (dominant): "RC1", "RC2" and "RC3" was placed on the proximal head of 1st, 2nd, and 3rd metacarpal. "RMT" and "RPT" was placed on a rigid body on thumb metacarpal and first phalange of the thumb (to observe thumb rotation). "RM1", "RM2" and "RM3" was placed on the distal head of the 1st, 2nd, and 3rd metacarpal. "RPP1", "RPP2" and "RPP3" was placed on the proximal inter-phalangeal joints of the 1st, 2nd, and 3rd fingers. "RPM2" and "RPM3" was placed on the distal inter-phalangeal joints of the 2nd and 3rd fingers. "RPD1", "RPD2" and "RPD3" was placed on the distal head of the distal phalange.

For left side (non-dominant): "LSH" was placed on the lateral part of the acromion. "LU1","LU2", "LU3" was a cluster of markers placed on the lateral face of the arm. "LEM" and "LEL" was placed on medial and lateral elbow epicondyle respectively. "LU" and "LR" was placed on the extern face of ulnar and radius 5 cm proximally from the wrist and "LWU" and "LWR" on ulnar and radius distal head respectively.

For left hand (non-dominant): "LC1", "LC2" and "LC3" was placed on the proximal head of 1st, 2nd, and 3rd metacarpal. "LMT" and "LPT" was placed on a rigid body on metacarpal and first phalange of the thumb (to observe thumb rotation). "LM1", "LM2" and "LM3" was placed on the distal head of the 1st, 2nd, and 3rd metacarpal. "LPP1" and "LPP2" and was placed on the proximal inter-phalangeal joints of the 1stand 2nd fingers. "RPM2" was placed on the second inter-phalangeal joints of the 2nd finger. "RPD1" and "RPD2" was placed on the distal head of the distal phalange.

Appendix.3. : Joint and movement label

Joint	Label	Movement
Shoulder	Shoulder-Add/Abd	Adduction/Abduction
	Shoulder-Flex/Ext	Flexion/Extension
	Shoulder-Pron/Sup	Pronation/Supination
Elbow	Elbow-Flex/Ext	Flexion/Extension
Wrist	Wirst-Add/Abd	Adduction/Abduction
	Wirst-Flex/Ext	Flexion/Extension
	Wrist-Pron/Sup	Pronation/Supination
Forefinger		
Metacarpophalangeal	First-MCP-Add/Abd	Adduction/Abduction
	First-MCP-Flex/Ext	Flexion/Extension
Proximal interphalangeal	First-PIP-Flex/Ext	Flexion/Extension
Distal interphalangeal	First-DIP-Flex/Ext	Flexion/Extension
Middle finger		
Metacarpophalangeal	Middle-MCP-Add/Abd	Adduction/Abduction
	Middle-MCP-Flex/Ext	Flexion/Extension
Proximal interphalangeal	Middle-PIP-Flex/Ext	Flexion/Extension
Distal interphalangeal	Middle-DIP-Flex/Ext	Flexion/Extension
Thumb		
Trapeziometacarpal	Thumb-TMC-Add/Abd	Adduction/Abduction
	Thumb-TMC-Flex/Ext	Flexion/Extension
Metacarpophalangeal	Thumb-MCP-Add/Abd	Adduction/Abduction
	Thumb-MCP-Flex/Ext	Flexion/Extension
Interphalangeal	Thumb-IP-Flex/Ext	Flexion/Extension

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