Human-Delivered Brushstroke Characterization using an Instrumented Brush Focused on Torque

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***Abstract*—Pleasant brush therapies may benefit those with autism, trauma, and anxiety. While studies monitor brushing velocity, hand-delivery of brush strokes introduces variability. Detailed measurements of human-delivered brushing physics may help understand such variability and subsequent impact on receivers' perceived pleasantness. Herein, we instrument a brush with multi-axis force and displacement sensors to measure their physics as 12 participants pleasantly stroke a receiver's forearm. Algorithmic procedures identify skin contact, and define four stages of arrival, stroke, departure, and airtime between strokes. Torque magnitude, rather than force, is evaluated as a metric to minimize inertial noise, as it registers brush bend and orientation. Overall, the results of the naturally delivered brushing experiments indicate force and velocity values in the range of 0.4 N and 3-10 cm/s, in alignment with prior work. However, we observe significant variance between brushers across velocity, force, torque, and brushstroke length. Upon further analysis, torque and force measures are correlated, yet torque provides distinct information from velocity. In evaluating the receiver's response to individual differences between brushers of the preliminary case study, higher pleasantness is tied to lower mean torque, and lower instantaneous variance over the stroke duration. Torque magnitude appears to complement velocity's influence on perceived pleasantness.**

***Index Terms*—brush, touch therapy, pleasantness, affective touch**

I. Introduction

Affective gentle touch can trigger a sense of calming [1]–[7], reduce anxiety [2], [8], and be therapeutic [2]. Such therapies have been shown to improve quality of life for cancer patients [9], ameliorate depressive symptoms [8], [10], [11], help with understanding autistic spectrum disorder [12], and improve infant development [4], [13]–[17]. Calming strokes, using either the toucher's hand directly or a brush, appear to affect pleasantness similarly [18]–[22], though studies often prefer brushes due to their consistent dimensions and mechanical properties. Brushstrokes are typically delivered either by trained human brushers or robotic devices, where the latter can afford reproducible trajectories, forces, and velocities. However, recent studies exploring the use of robotic devices find discrepancies between their motion paths and those of human brushers [23]. For instance, as the duration of a robotic delivered brushstroke is determined by a preset velocity, it is unable to deliver a constant stroke length at different speeds as it follows a circular sweep path.

When pleasant brushing is delivered by trained brushers [18], [19], [24]–[29], they attempt to maintain consistent velocity and force, but few methods in practice measure the achieved strokes, and individual differences are evident between trials and brushers. As such, it is challenging to study exactly how brush velocity affects pleasantness with sources of variance at play. Research into the relationship between brushing velocity and pleasantness has widely reported an inverse u relationship, with peak pleasantness experienced in the range of 3-10 cm/s [30]. However, experimental procedures can differ in their specification and achievement of stroke length, brush tip size and stiffness, force rates, and sweep path, etc. Indeed, a review of five prior studies found that the inverse u relationship between velocity and pleasantness significantly differs between experimental paradigms [31]. Such reports suggest that factors other than velocity alone are likely to affect pleasantness.

Uncovering additional brushing metrics of relevance, such as torque and trajectory, may afford a richer understanding of the factors driving pleasantness. In this study, we develop an instrumented brush to evaluate individual differences across metrics underlying the physical interactions during human-delivered brushing. Utilizing the device, we conduct a preliminary case study to tease apart the importance of such factors on pleasantness. Such engineering definitions and measurements may improve our understanding of the physical factors that underlie brushing and eventually lead to reproducible standards in conducting pleasant brush therapies.

II. Methods

This work develops an instrumented brush to measure the physical interactions in human-delivered pleasant touch, and to evaluate the impact of their variance between brushers upon receiver pleasantness. The metrics include force, torque, and displacement, each in six-axes. We develop algorithmic procedures to identify skin contact and classify four brushstroke stages, i.e., arrival at skin contact, stroke on the skin surface, departure from skin contact, and airtime between departure and arrival. In a series of experiments with 12 brusher participants, we evaluate the utility of each contact metric in the context of the four brushstroke stages, their magnitude, variance, and correlations between participants, and the impact of their magnitude and variance upon pleasantness reported by a receiver. In each of the five recorded trials, participants brushed a receiver's forearm for

30 sec, about 10 brush strokes per trial, in a unidirectional pattern.

A. Instrumented brush apparatus

The instrumented, hand-held brush (Fig. 1A) is comprised of a custom 3D printed adapter for the brush, flat head cosmetic brush (2.7 cm wide, 2.3 cm thick, Mudder, USA), load cell (Nano17, ATI Industrial Automation, Apex, NC, USA), 3D printed brush handle, and an electromagnetic tracking system (Flock of Birds, Ascension trakSTAR/driveBAY, USA). Orientation markers were incorporated into the 3D printed adapters to ensure the contact tip and handle were aligned and maintained consistent sensor orientation throughout the experiments. An interchangeable tip allows for the use of different contact mediums through a 3D printed screw attachment that can be attached to any contact medium. The construction of the instrumented brush aligns the load cell with the brush tip so that a bend in the brush records a torque measurement and ensures that no skin contact reports zero torque.

The load cell measures force in six directions (Fig. 1B, D) and achieves 1/320 N resolution and 30 N range, at a 300 Hz sampling rate. It also measures torque with 1/64 N·mm resolution and 120 N·mm range. The displacement, in addition, can be monitored in six directions, with 1.4 mm root mean square (RMS) resolution and 1.5 m range, at 300 Hz sampling rate. In addition to its x, y, and z translational displacements, brush orientation is recorded as Euler angles (roll, pitch, and yaw) for a 0.5-degree RMS. Raw position is captured at the local tracker embedded in the brush handle, in reference to the electromagnetic field generator. To solve the time synchronization between the force and displacement sensors, the sensors' recorded time was sourced from the computer clock. The timetable per sensor was then synchronized over the entire time range on a linear scale.

B. Position correction procedure

A coordinate frame adjustment translated the raw position of the brush handle to the brush tip. This adjustment was made to ensure that displacement due to rotational motion was preserved, in which the brush handle end does not change position, but the brush tip does. The preservation of this movement is important as rotational movement is commonly observed in both robotic and human-delivered brushing. Recorded Euler angles (roll, pitch, and yaw) determine the directional vector of the brush, while translation length is equal to the distance between the electromagnetic tracker and brush tip. The position corrections (x_c, y_c, and z_c) using Equation 1 were added to measured positions (x, y, and z) to calculate the stroke path of the brush tip based on α=roll, β=pitch, γ=yaw, and l=brush length (cm).

$$\begin{bmatrix} (\cos\beta\cos\gamma) & (-\cos\beta\sin\gamma) & (\sin\beta) & 0 \\ (\sin\alpha\sin\beta\cos\gamma+\cos\alpha\sin\gamma) & (\sin\alpha\sin\beta\sin\gamma+\cos\alpha\cos\gamma) & (\sin\alpha\cos\beta) & 0 \\ (\cos\alpha\sin\beta\cos\gamma+\sin\alpha\sin\gamma) & (\cos\alpha\sin\beta\sin\gamma+\sin\alpha\cos\gamma) & (\cos\alpha\cos\beta) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 0 \\ 0 \\ l \\ 1 \end{bmatrix} = \begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} \quad (1)$$

C. Rational for Use of Torque Magnitude

The method of contact detection and stage classification utilizes torque magnitude to detect surface contact and to define the brushstroke stages. Example data is shown for all six torque and force axes for a series of four concurrent brush strokes made by one study participant (Fig. 1C, D). As is indicated in Fig. 1E, F, we evaluate torque and force magnitudes, i.e., the square root of the sum of the squares of each axial component. These quantities strongly, but not exclusively, reflect changes in T_y and $-F_z$.

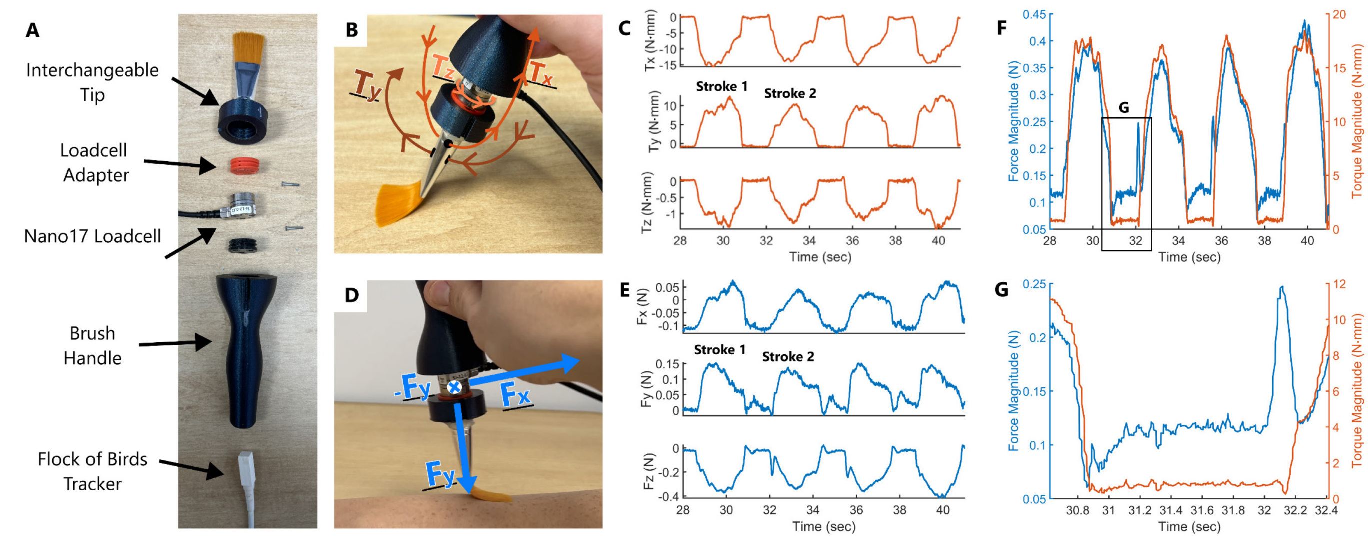

Fig. 1. Overview of instrumented brush. (A) Components of the instrumented brush, including the load cell (force) and electromagnetic tracker (displacement). (B, D) Following the directional notation, the load cell measures multi-axis components of torque (N·mm) and force (N). (C, E) Example data for all torque and force axes for four brush strokes made by a study participant. (F) Torque and force magnitudes, which heavily but not exclusively reflect changes in T_y and $-F_z$, are plotted against each other. The magnitude of their peaks align, though the troughs are more distinct and steady for torque. Indeed, force normal to the brush contact surface F_z has been commonly reported in prior studies but is susceptible to noise from acceleration and angular changes in brush positioning, which distorts periods of non-contact, especially at low force. (G) A highlighted view of the no contact zone from panel F is indeed noisier at no contact for force magnitude as compared with torque magnitude. Due, in part to its ability to distinguish contact and no contact more clearly, we rely upon torque magnitude in contact identification and brush stage classification. Moreover, as the rotational equivalent of linear force, torque magnitude is naturally more representative in considering brush strokes.

Compared with its force counterpart, torque magnitude is advantageous in the context of a brushstroke because it is more robust to inertial noise and preserves the rotational aspects of contact. In Fig. 1F, G, torque magnitude maintains a more constant and distinct no contact zone compared to force. This is likely due to force sensing errors influenced by brush acceleration.

Torque is a more robust and reliable measure in defining contact start and end with lower noise because it requires a moment around the load cell; the brush tip must bend to register a measurement. Indeed, prior studies have only reported force in the direction normal to the brush contact surface (F_z) [23], [25], [30]. These works do not indicate if angular corrections are made to resolve gravitation load due to brush orientation.

D. Brush to skin contact detection

A method to define contact between the brush tip and the receiver's skin surface was developed. Per trial, contact and no contact thresholds are calculated by first determining local minima and maxima of smoothed torque (Fig. 2A), which is filtered at 20 samples and smoothed using a moving mean (0.05 factor). Then, in Fig. 2B, the upper "contact threshold" is defined as 60% of the minimum of the series of local maxima from Fig. 2A. The lower "no contact" threshold is three times the median value of the local minimum. These thresholds are calculated for each participant per trial, where a trial is a series of consecutive brush strokes (~10) completed by a brusher in 30 sec. Defining thresholds as such with a large gap between no contact and contact seeks to remove noisy readings where a small magnitude of torque is registered, but no contact takes place. At the conclusion of this procedure, the points with positive torque above the "contact threshold" line in Fig. 2B are definitely making contact and included as such in the analysis.

E. Brushstroke stage classification

We algorithmically define brushstroke stages of arrival, stroke, departure, and airtime (Fig. 2E, upper). A multi-step definition process begins with 1) the contact end points at the no contact threshold in Fig. 2B, which ensures that arrival does not occur after contact begins and departure does not end before contact ends. Then in Fig. 2C, we capture 2) the peaks in the rate of change of torque magnitude over the time course of the stroke (dTmag local max), 3) the stationary point in the rate of change of torque magnitude when the derivative is zero (dTmag stationary points), and 4) the rate of change of displacement in the Y direction (dY stationary point) (i.e., longitudinally down the arm of the receiver).

In terms of the four brushstroke stages (Fig. 2D, E), the arrival of the brush at skin contact is characterized by the change in direction to begin brushing (dY stationary point) preceding the beginning of torque measurement. The large ramp-up of torque magnitude during initial contact allows the use of change in torque (dTmag local max) to mark the end of the approach stage. Next, the stroke stage is characterized by consistency in torque compared to the transitional stages of approach and arrival.

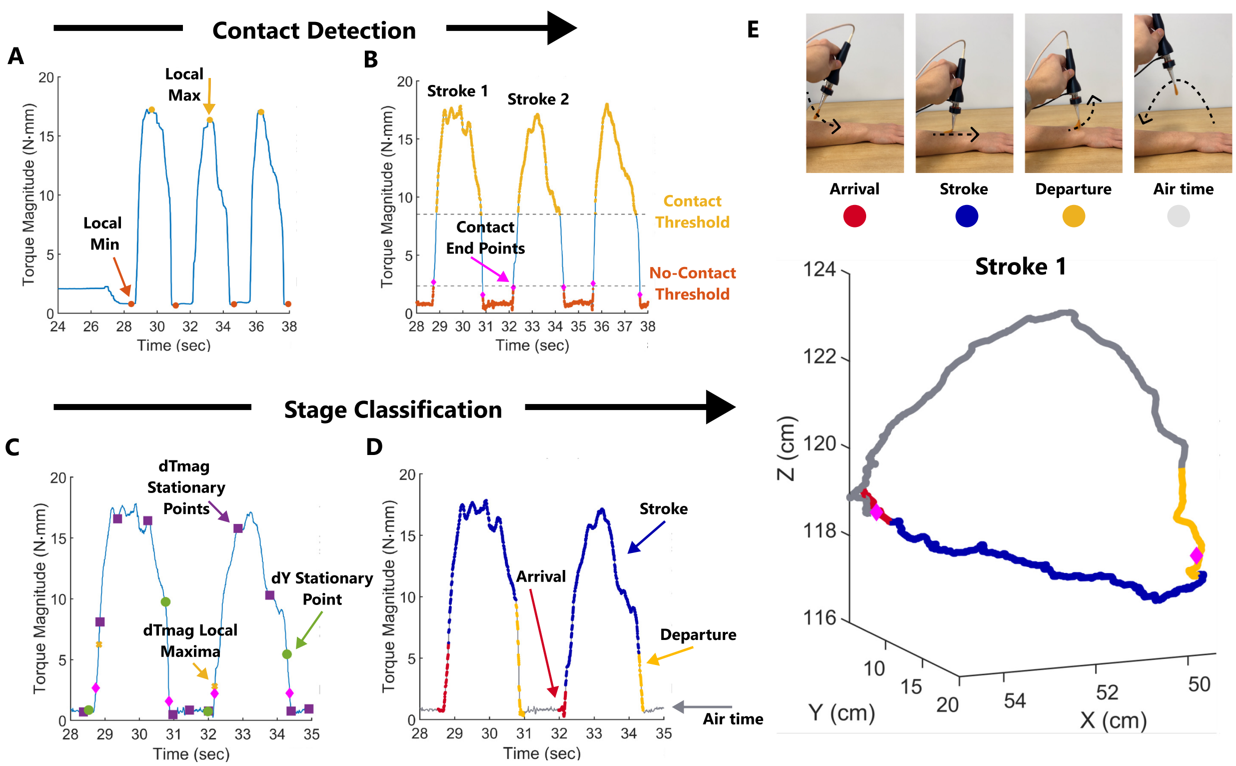

Fig. 2. Brush tip to skin surface contact detection and definition of four brushstroke stages. (A) The local maxima and minima of smoothed torque magnitude used as contact and no-contact threshold determinants. (B) Using the thresholds from panel A, the torque data is sorted into contact and no contact points to determine the beginning and end of brushstroke contact, with contact end points denoted. (C-D) The torque magnitude data is sorted into the four brushstroke stages using the annotated and labeled points. With additional description in Methods II.E., the unidirectional pattern of brushing uses the change in dY stationary point as a point of arrival and departure. The dTmag local maxima marks the end of arrival (beginning of stroke) as the brush begins to bend and is level in angle of approach. The dTmag stationary points mark the end of departure as the brush is not bending right when it leaves the skin. Contact occurs between arrival end and departure begin.

Then, the departure of the brush from skin contact is characterized by a change in brushing direction (dY stationary point) to reset for the next stroke, and a zero derivative torque measurement as contact ends (dTmag stationary point). The beginning of departure is marked by an inflection point in the y direction (dY stationary point) as we found the brusher begins to reset before the end contact. The end of departure is when torque stops decreasing (dTmag stationary point), occurring after contact ends. This end marks the beginning of airtime, where the brusher is resetting their position for the next stroke.

These defined brushstroke stage markers are overlaid on the torque magnitude plot as stages of arrival, stroke, departure, and airtime (Fig. 2D). Moreover, in Fig. 2E, the resultant brush stroke stages in the same color hues are shown in the positional space. One can observe the stroke follows a fairly continuous line as the brusher moves down the receiver's forearm, and stages of arrival and departure before and after the stroke, with a long arc of airtime as the brush is repositioned.

III. Experiments

A preliminary human-subjects case study was conducted to evaluate the instrumented brush, its output metrics, and the defined brushstroke stages. In the first part of the study, the physics of human-delivered brushing are examined, in terms of aggregate trends for the cohort and individual differences between participants. In the second part of the study, we examine how individual differences of untrained brushers in the metrics underlying the physical interactions affect a receiver's perceived pleasantness.

A. Experimental setup

Each participant used the instrumented brush to pleasantly brush the receiver's forearm. One touch receiver was the recipient of all brushing trials and reported continuous pleasantness ratings (-50 to 50). To reduce external influences, an opaque curtain was setup between brusher and receiver to eliminate visual cues. The receiver wore noise cancelling headphones. The receiver's left arm was positioned in a mold in the same spot and orientation, and markers 10 cm apart were drawn on the arm within which the brusher was asked to begin and end brush contact.

B. Participants

The study was approved by the local institutional review board. Twelve individuals (5 male and 7 female, mean age = 26.1, SD = 3.2) participated as brushers in the study. All reported being right hand dominant, and all provided written informed consent. We note that the receiver reported pleasantness ratings for seven of the twelve participants. Responses for five participants were not recorded as the pleasantness survey was implemented after their physical interaction data had been collected.

C. Experimental Procedures

Each brusher participant initially completed three 30 sec self-brushing trials to practice delivering brush strokes while directly feeling its effects. The brusher was instructed upon the direction to hold the brush, i.e., flat side facing down the forearm towards the hand. Each brusher was then instructed to "pleasantly brush the receiver's arm in a unidirectional manner from elbow to hand along the forearm in the constrained area as marked." The brusher was asked to begin brushing and then, after 30 sec, was asked to conclude. This procedure was repeated for a total of five trials for each of the 12 brushers, resulting in 60 total trials. The receiver reported a pleasantness rating at the end of each trial via a continuous scale from unpleasant to pleasant for seven participants. Between participants, the receiver washed his forearm with soap and water for 2 min and sat without brushing stimulation for 5 min.

IV. Results

Each experimental trial for each participant was separated into individual brushstrokes from which measurements of torque, force, velocity, and stroke length were evaluated. Averages per stroke for these four factors across all trials and participants (664 strokes = 12 participants * 5 trials * ~10 strokes per trial), as calculated in sections II.D., are aggregately shown in Fig. 3A. Note that participant 2's data was removed due to measurement error, with a reported force mean of 2, double the maximum force of the 11 participants and outside the outlier Cook's distance. The data were then analyzed with all strokes aggregated by mean across the 4 measures for each individual brusher, and in relation to pleasantness ratings.

A. Aggregate physical interaction metrics for all participants

In Fig. 3A aggregate data for all participants and trials is shown, with over half delivering a brush velocity of 3-10 cm/s, agreeing with prior studies [30]. A median force magnitude of 0.36 N was measured, also agreeing with prior studies [23], [25], [30]. Additional metrics developed in this work, namely torque magnitude and stroke length, exhibited median values of 13.40 N·mm and 12.42 cm, respectively, with the latter deviation observed despite the 10 cm specified distance. Further statistical analysis in Fig. 3B shows neither a Pearson correlation between force magnitude and velocity (r = 0.08), nor between torque magnitude and velocity (r = 0.45), but a moderate correlation between torque magnitude and force magnitude (r = 0.6) was observed. The torque and force correlation is expected as torque is the rotational equivalent of linear force. However, the lack of correlation of torque and force with velocity, not previously studied, indicates a unique contribution of these metrics.

B. Individual differences in metrics between brushers

The large variability observed at the population level in Fig. 3A is further examined among individual brushers (Fig. 3C-E). We examine individual participants and combinations in a case study. While some participants maintain lower variance across trials in torque, force, and velocity (e.g., 1, 6), others show notable inconsistencies (4, 8). In specific, median torque magnitudes for participant 4 (21 N·mm, $p<0.0001$, using a one tail Mann-Whitney u test with a Bonferroni correction for Type 1 errors) and participant 8 (20 N·mm, $p<0.0001$) are significantly greater than the aggregate torque magnitude (13 N·mm). We also observe a significantly higher force magnitude for participant 4 (0.55 N, $p<0.0001$), relative to the aggregate magnitude (0.36 N). Velocity measures split the sample into two groups: 7 participants brushed in the 3-10 cm/s range, which has been shown

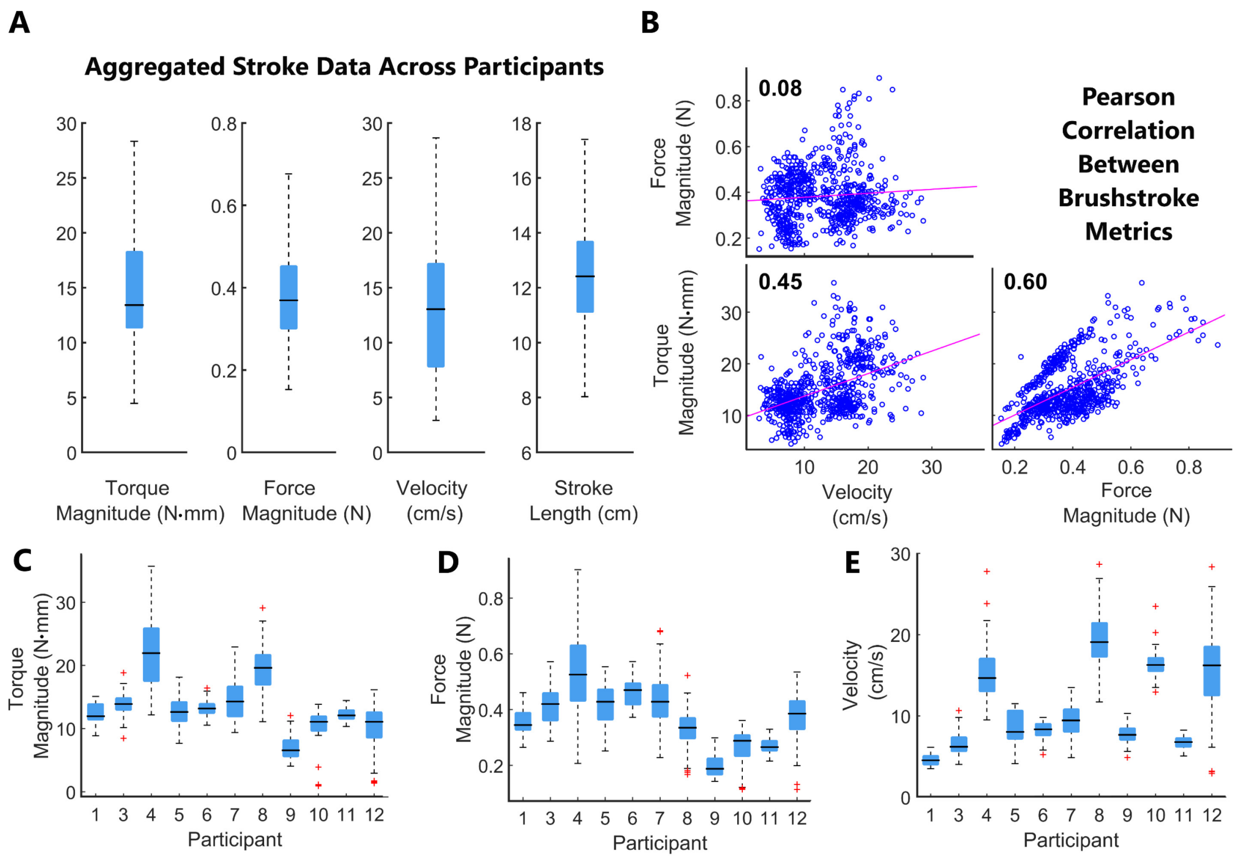

Fig. 3. Physical interaction metrics for all participants aggregated and between touchers. (A) Brushstroke data aggregated across all brushers were derived from measurements of torque magnitude, force magnitude, and velocity. (B) Correlations between force magnitude, torque magnitude, and velocity were used to understand the relationship between the contact metrics during brushstroke contact. Force and torque magnitude show no relationship with velocity. Force and torque are strongly correlated, due to torque being the rotational equivalent of linear force. (C-E) Per participant breakdown per contact metrics indicates high variability across participants, as well as often within participant. Note that participant 2 was removed due to measurement error.

to be the most pleasant range in prior studies [30]. The remaining four high velocity brushers contained the lowest pleasantness rated brusher, participant 4 (19.1 cm/s, $p<0.001$ from aggregate).

C. Pleasantness ratings relative to interaction metrics

Pleasantness ratings reported by the receiver at the end of each trial for seven participants range from 17 to 43 on a continuous scale from -50 (least pleasant) to 50 (most pleasant) (Fig. 4A), following prior convention [25], [32]. All ratings were above zero, i.e., no brushers delivered unpleasant strokes. Variability in pleasantness is measured between participants and within individual trials. For further examination in a case study, we compare a statistically significant difference ($p<0.01$) for brushers with the lowest median pleasantness in participant 4 (19) and the highest median pleasantness in participant 6 (34). These two participants exhibit statistically significant differences in torque magnitude ($p<0.0001$), force magnitude ($p<0.001$), and velocity ($p<0.0001$) (Fig. 4B), with participant 4 recording higher magnitudes across all three metrics.

For comparison, we chose a second case between two participants with no statistically significant differences, i.e., participants 1 and 6 (Fig. 4A). While a statistically significant difference is observed between their force magnitude and velocities (Fig. 4C, $p<0.0001$ and $p<0.0001$ respectively), their torque magnitudes are not statistically different. Such case study comparisons between participants 4 and 6, and 1 and 6, suggest that torque magnitude might contribute to pleasantness, though the sample size is too small to derive definitive, broader conclusions.

D. Pleasantness and instantaneous changes in brushstroke

In addition for the potential for average torque over a trial to impact pleasantness , we examined instantaneous torque over the course of individual brushstrokes between the two participants who produced the most distinct in pleasantness ratings 4 and 6. These brushers exhibit significantly different torque magnitude and variance over the course of their brushstrokes (Fig. 4D-F).This can be directly observed in torque magnitude along the motion path of single brushstroke (Fig. 4E-F) of either participant, with less variance in torque magnitude throughout contact duration for participant 6, as compared to participant 4. The instantaneous changes over the duration of single brushstrokes, in addition to its average in section IV.C., may also be a factor to drive perceived pleasantness.

V. Discussion

Pleasant brush therapies are increasingly being shown to benefit those with depression, trauma, and anxiety [1], [2], [4],

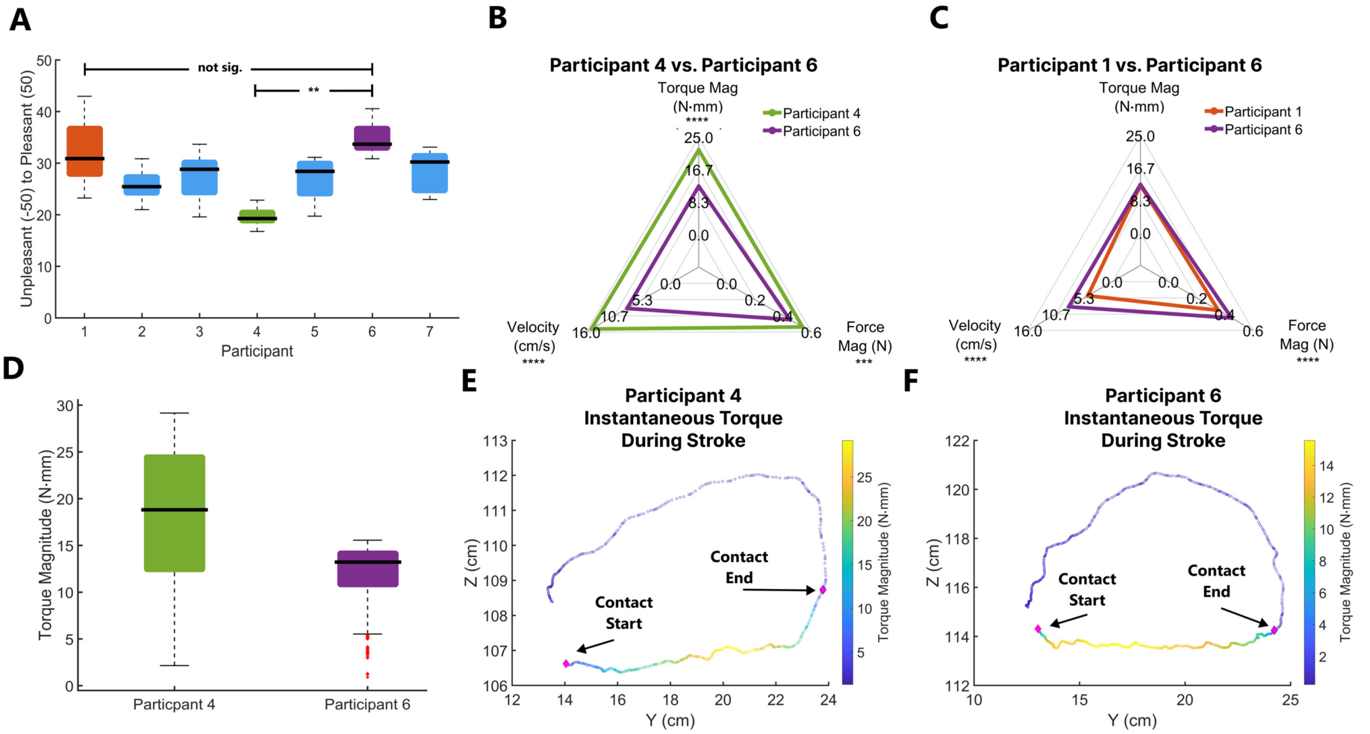

Fig. 4. Pleasantness ratings relative to physical interaction metrics; case study of most and least pleasant brushers. (A) Pleasantness ratings of the touch receiver in response to seven participants. No brusher delivered an unpleasant brushstroke trial. The brusher with lowest median pleasantness was significantly different from the brusher with highest median pleasantness (participants 4 and 6). A second set of participants (1,6) was chosen because they generate non-significant pleasantness differences. (B-C) Participants 4 and 6 are distinct in all three metrics, while 1 and 6 do not differ in their torque magnitude. (D) The significant difference in instantaneous torque over the course of their brushstrokes is shown in both magnitude and variance of participant 4 and 6. Both brushers ramp up during arrival, hit some consistency during stroke, and ramp off during departure. (E-F) A key difference between participants 4 and 6 is their torque variance during the stroke, with participant 6 maintaining peak torque for the majority of the stroke, whereas participant 4 greatly varies in torque application across stroke. Significance levels correspond to *p<0.05, **p<0.01, ***p<0.001, ****p<0.0001 derived by paired-sample Mann–Whitney U tests with a Bonferroni correction.

[8]. While most studies use expert touchers to deliver brush strokes and monitor brushing velocity, the hand-delivery of brush strokes introduces variability [21], [22], [24]–[26], [30]. As such, detailed measurements of the physics of human-delivered brushing may help understand the nature of such variability and its potential impact on a touch receiver's pleasantness. To begin to explore these questions, this work instruments a brush to measure multiple physical interaction metrics and define four brushstroke stages of arrival, stroke, departure, and airtime between strokes. An initial case study consisting of a series of human-subjects experiments suggests individual differences among brushers may influence the production of torque and force magnitudes and velocity. In a case study with a limited number of brushers, we begin to observe connections between torque magnitude and psychophysical pleasantness ratings, which may play a role, in addition to that well established for velocity. In particular, higher pleasantness may be tied to lower mean torque, and less instantaneous variance over the stroke duration. In this way, torque magnitude may independently complement, though further confirmatory experiments with a greater number of participants are required.

Brushing with the hand-held instrumented device produces measurements that align with existing protocols. In particular, aggregate physical interaction metrics for all participants of 0.36 N and most participants brushing at 3-10 cm/s, match with those of prior literature for gentle pleasant brushing [23], [25], [30], [31] and robotic brushing studies [25], [30]. Since there has been little prior work to quantify non-expert human-delivered brushing, this device and measurements provide novel validation for existing protocols. While aggregate averages align with existing work, we observe significant variance in measured metrics within and between participants, trials, and brushstrokes.

In beginning to investigate such variance in brushstroke interactions between participants, we find that subtle differences in brushing physics between participants appear to affect receiver pleasantness. Namely, we measure quantifiable differences in delivery of torque magnitude over the course of single brushstrokes (Fig. 4D-F). Brusher participants that maintain stable torque delivery over the entire contact duration (~2.5 sec) are rated as being more pleasant than their less-consistent counterparts. While a degree of variability is inherent to human-delivered brushing, these results suggest that excessive variability in torque may decrease perceived pleasantness. These findings warrant future studies with larger and more diverse participant pools to measure variability in the physics of brushstrokes and understand its contribution to a receiver's perceived pleasantness.

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