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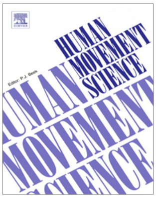

The smoothness of unconstrained head movements is velocity-dependent

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ABSTRACT

Non-smooth, irregular movements reported in persons with neck pain have been suggested to signify motor impairment. However, irregular movements are additionally observed during slow movements in healthy participants. We therefore examined whether the smoothness of head movements is related to the movement speed in 26 healthy participants. Six unconstrained small and large amplitude head movements were completed in the sagittal plane at three different self-chosen speeds. Kinematic variables were calculated from position data and overall smoothness of the movement was assessed by the normalized jerk cost (NJC). Relationship between NJC and average movement angular velocity was analyzed using a mixed factor model. Movement duration, angular velocity, NJC and number of submovements differed significantly between speed conditions for all movement directions and amplitudes (all $p < .05$). We found a strong relationship between the average angular velocity and NJC across all movement directions and amplitudes (all $p < .0001$). Large amplitude movements showed higher NJC for a given movement velocity than small amplitude movements ($p < .001$). We have shown that the smoothness of head movements is strongly related to the movement velocity, thus fast movements are smooth while slow movements are jerky. In addition, movements of larger amplitude are less smooth than movements of smaller amplitude.

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1. Introduction

Natural, unconstrained voluntary movements in humans are normally smooth and exhibit a near symmetrical, bell-shaped velocity profile containing a single velocity peak with approximately equally long acceleration and deceleration phases. Such profiles have been reported in studies addressing movements such as reaching, pointing and grasping and across several species (Aflalo & Graziano, 2007; Alstermark, Lundberg, Pettersson, Tantisira, & Walkowska, 1993; Atkeson & Hollerbach, 1985; Ostry, Cooke, & Munhall, 1987; Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1990). When temporal or spatial accuracy constrains are introduced, the movements become less smooth, and irregularities in the velocity profiles have been reported across various species (Milner & Ijaz, 1990; Roitman, Massaquoi, Takahashi, & Ebner, 2004; Thompson, McConnell, Slocum, & Bohan, 2007). The irregularities within the movements have been suggested to be submovements, appearing as down scaled, bell-shaped velocity peaks (Crossman & Goodeve, 1983; Krebs, Aisen, Volpe, & Hogan, 1999; Milner, 1992).

Movements of patients with neurological injury and diseases are less smooth compared with healthy controls and are characterized by submovements within the velocity profile (Rohrer et al., 2002; Smith, Brandt, & Shadmehr, 2000; Teulings, Contreras-Vidal, Stelmach, & Adler, 1997; Tsao & Mirbagheri, 2007). Also in musculoskeletal neck pain, movements are shown to be less smooth and more irregular compared with controls without pain (Feipel, Rondelet, LePallec, DeWitte, & Rooze, 1999; Grip, Sundelin, Gerdle, & Karlsson, 2008; Sarig Bahat, Weiss, & Laufer, 2010; Sjölander, Michaelson, Jaric, & Djupsjöbacka, 2008). Consequently, increased irregularity and reduced smoothness of movement as compared to control situations have been considered a sign of altered motor behavior and impaired motor performance (Sjölander et al., 2008; Smith et al., 2000; Teulings et al., 1997).

However, it has been observed in healthy participants that when relatively unconstrained movements are completed with reduced velocity, irregularities appear on the velocity tracings (Darling, Cole, & Abbs, 1988; Milner, 1992; Milner & Ijaz, 1990; Morasso, Ivaldi, & Ruggiero, 1983). For example, Morasso et al. (1983) noted that while planar pointing movements performed at natural speed displayed a single peaked velocity profile, more velocity peaks appeared at slower movements. Similarly, in a time-constrained pinching task, Darling et al. (1988) reported that while 100 ms movements of the thumb and index finger were completed with a single submovement, 200–400 ms pinches contained a series of submovements. Although no statistical analysis of smoothness or irregularity between movements velocities were completed in either of these studies, the descriptions of increased irregular velocity profiles at relatively slow movements imply a relationship between movement velocity and smoothness. Using spatio-temporal constrained arm movements, van der Wel, Sternad, and Rosenbaum (2009), found an overall statistically significant effect of standardized movement times on the number of velocity peaks within a movement. Although the accuracy constraints in their study were relatively limited, the arm movements were completed in a continuous, rhythmic mode and paced by a metronome, which previously has been reported to reduce movement smoothness as compared to unpaced movements (Balasubramaniam, Wing, & Daffertshofer, 2004). Thus, these results accomplished for constrained movements may not directly apply to unconstrained movement. Although the above studies strongly suggest that a relationship between movement smoothness and velocity exist, to our knowledge, no statistically based evaluation of such a relationship in simple, unconstrained movements have been published. Of particular interest was to examine a relationship between smoothness and velocity in head and neck movements. As noted above, these movements are previously reported to be less smooth in humans with musculoskeletal neck pain as compared to unimpaired controls and this finding has been interpreted as a sign of altered motor control. However, since these movements were reported to be less fast and have less amplitude than for unimpaired control participants (Grip et al., 2008; Sarig Bahat et al., 2010), we wanted to examine whether the movement velocity and amplitude could be main sources of irregularity in head movements.

The goal of this study was thus to examine the relationship between movement smoothness and velocity of unconstrained movements in healthy human participants, and particularly to consider the case of head movements. We tested the hypothesis that overall movement smoothness is related to movement velocity by systematically altering the velocity of movements in separate trials and for several different movement directions and amplitudes.

2. Methods

2.1. Participants

Twenty-six healthy men ($n = 12$) and women ($n = 14$) of 36.1 ± 8.4 ($M \pm SD$) years of age participated in the study. The participants were 173.8 ± 8.3 cm tall, weighed 75.0 ± 12.9 kg and the BMI was 24.7 ± 2.9 kg/m^2, all values close to the Norwegian average values. None of the participants in the study suffered from neurological or rheumatic disorders, had current head or neck complaints or had experienced recurrent periods of neck or head pain exceeding one week during the previous 2 years. The study was approved by the Regional Committee for Medical and Health Research Ethics, and all participants signed an informed consent form for participation in the study.

2.2. Test chair

A custom-made chair was constructed in order to be able to isolate the head and neck movements. The participant sat on an adjustable seat with a right-angled back support that was individually height-adjusted. The feet support was adjusted to keep the knee angle at approximately 90°. The participants were secured tightly to the chair by Velcro bands applied transversely around the arms and upper torso, as well as across the hips.

2.3. Procedures

All participants completed one separate training session to familiarize to the testing procedures 1–2 weeks prior to the measurements. All tests were supervised by two examiners. In sitting the participants were instructed to position themselves in their individual neutral position (NP) of the head when looking straight forward at the wall approximately 120 cm in front of the participants. At the participant's individual focus point on the wall, a 15 mm diameter dark blue dot was applied as reference for the NP. As the present study was the first using the presented experimental setup from our lab, we quantified the uncertainty of the outcome variables by testing the reliability of the measurement. Twelve participants who did not differ in age or anthropometrics from that of the other participants were retested two hours later using identical procedures as during the first test.

2.3.1. Movement directions and amplitudes

With the eyes open, the participants completed four movements corresponding to approximately half of their full range of motion and these were defined as small amplitude movements: forward flexion from NP (FFN), extension back to NP (EBN), extension from NP (EFN) and flexion back to NP (FBN). The movements started from the NP and stopped at the fully flexed or extended position (FFN and EFN) or started at the fully flexed or extended position and stopped at the NP (EBN and FBN). Additionally, 12 of the participants (7 men, 5 women) who did not deviate in age or anthropometrics from that of the other participants completed two full ranges of movements (100%) in the sagittal plane. These movements were defined as large amplitude movements: full extension in the posterior direction starting from a fully flexed position (EF) and full flexion in the anterior direction starting from a fully extended position (FF).

2.3.2. Movement speed conditions

To obtain a large range in movement angular velocity for each participant, they were tested at three different speed conditions. First, the participants were instructed to complete all the movements in a pace corresponding to what they perceived as their normal speed and was termed preferred speed (P), then with half of their preferred speed, termed slow speed (S) and finally with their maximum speed (M). To put as little constraints on the movements as possible, the participants were not given any feedback on their performance during testing. For the S speed condition, the participant tended to move more slowly than half of the P speed. The order in which the direction of movements were performed was randomized for each participant. The participants were allowed to practice the movement directions and speed conditions before the test started. The participants completed 3 trials per speed condition for each direction and these were averaged for further analysis. All trials were accepted, except if the participants expressed that the movements deviated from what they had intended to do, then retrials were performed. In sum, participants performing the small amplitude movements completed a total of 36 trials, while the participants that in addition performed large amplitude movements completed 54 trials.

2.4. Kinematics

2.4.1. Sensor placements

Position data were sampled using an electromagnetic motion tracker (Liberty, Polhemus Inc. Colchester, Vermont, and USA). The system's reference frame, defined by the transmitter, was positioned such that the axis of *Z* was vertical and the axis of *x* and *y*, respectively, were parallel to the sagittal and frontal planes of the participant. Three sensors were placed on the head–neck in the following configuration: A sternum sensor was placed 15 mm caudally to incisura jugularis (p1), a second sensor was placed above proc. spinosus C7 (p2) and the third sensor (p3) was placed 5 mm above the arcus superciliaris (Fig. 1A). A fourth virtual point (p4) was created at the instantaneous axis of rotation C7 (IARC7, see procedures below), to measure the angular position of the head–neck from its center of rotation. The head orientation angle was calculated as the angle between the horizontal line and the vector from p4 to p3. Hence, the rotation of the vector around the *y*-axis defined the movement for the head and neck complex.

2.4.2. Radiography and determination of the instantaneous axis of rotation

To be able to determine the position of IARC7 we used radiograph images and calculated the placement relative to that of p1 and p2. Lateral radiographs (DigitalDiagnost, Philips) were taken from a separate population consisting of 31 (14 women) healthy participants without neck complaints (age 38.3 ± 11.0 years; height 177.7 ± 9.9 cm; weight 76.1 ± 13.3 kg) in the standing position using a film focus distance of 150 cm. Two dummy metal sensors with identical dimensions as the original sensors

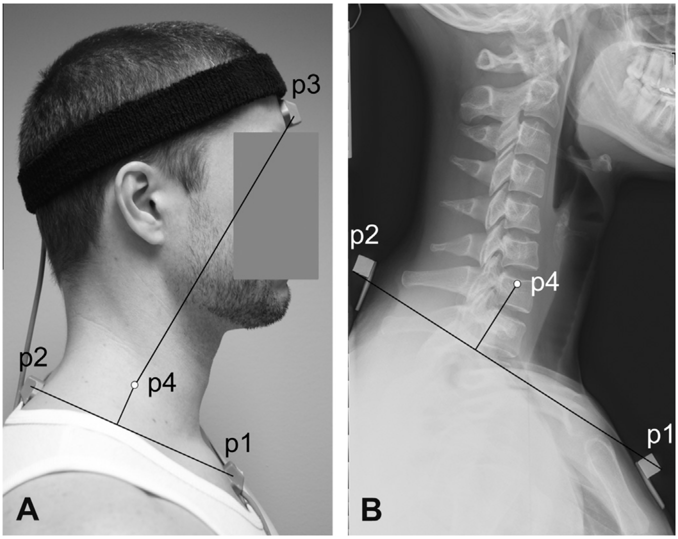

Fig. 1. A. The configuration of the three position sensors (p1, p2 and p3) and the fourth virtual point (p4) at the instantaneous axis of rotation C7 used for determination of head-neck movement from its centre of rotation. B. Lateral radiograph illustrating the method for construction of the virtual point (p4) relative to the p1 and p2 sensors.

were placed on p1 and p2 as described above, and used as reference. Radiographs were imported to the ImageJ software, version 1.31 (Rasband, W.S., National Institute of Health, USA) and the IARC7 was estimated and marked on the image according to the procedures of Amevo, Worth, and Bogduk (1991). The position of the IARC7 was measured relative to that of the dummy sensors. First, a line between the two dummy sensors (p1 and p2) was drawn and measured (180.4 ± 15 mm, *M* ± *SD*). A normal from the point of IARC7 to the interception with this line were subsequently drawn. The distances p1 – point of interception and the distance p4 (IARC7) – point of interception were normalized to the length of p1–p2 (57.2 ± 2.9% and 19.8 ± 4.5%, respectively) (Fig. 1B). There were no gender differences for these relative values. Hence, these mean relative measures were subsequently applied in the establishment of the individual p4 (IARC7) in the present study. The position of p4 was fixed relative to that of the p1, consequently; any positional changes for the p1 (sternum) would be similarly reflected in p4.

2.4.3. Signal reduction and data analysis

Position data were sampled at 240 Hz for each channel and analyzed off-line in MatLab. The signals were filtered using a quintic Woltring spline with a cutoff frequency of 6 Hz, chosen subsequent to a residual analysis (Winter, 2005). The quintic spline additionally defines the higher order derivatives (velocity, acceleration and jerk). Since the choice of threshold defining the movement onset and offset based upon relatives of the peak velocity will affect the kinematic variables in the study, comparative analyses using 4% and 10% of peak angular velocity as thresholds were conducted for the EFN movement direction. We also examined whether both thresholds could detect a relationship between movement velocity and smoothness. As the 4% threshold incorporates a larger part of the movement than the 10% limit, we chose to use 4% of peak angular velocity as the threshold for start and stop in this study. If the signal fluctuated across this 4% threshold, the final crossing was used for the offset. Movement duration and displacement were respectively the time and angular position difference between the movement onset and offset. To examine the angular velocity profile for regularity, the number of submovements within trials were counted and defined as the periods between two subsequent zero-crossings of the acceleration signal in direction from negative to positive values (Ketcham, Seidler, van Gemmert, & Stelmach, 2002). To measure the overall smoothness of the movement, we calculated the normalized jerk cost (NJC) according to Teulings et al. (1997), i.e., $\surd(\frac{1}{2} \int \mathrm{dt}\, j^2(t) \times \text{duration}^5/\text{displacement}^2)$, where “j” is the third derivate of position. The NJC is a unit-free measure and normalized for both duration and displacement, two factors that are known to strongly affect the jerk cost function of a movement (Schneider & Zernicke, 1989). Consequently, the NJC allows for comparison of the smoothness of movements across diverse durations and displacements. Large values signify reduced smoothness and low values signify increased smoothness. Hogan and Sternad (2009) showed, using a mathematical model, that the NJC scores increase both with increasing number of speed peaks in the movement and the magnitude of speed fluctuations between speed peaks, in consequence displaying the efficacy of the NJC to measure both smoothness and non-smoothness.

2.5. Statistics

Data are given as mean ± *SD*. To test for differences for the outcome variables between the S, P and M speed conditions within a given movement direction and movement amplitude, we used one-way repeated measures ANOVA and Bonferroni post hoc tests. The independent, within-subject factor was speed conditions and the dependent factor was the kinematic outcome variables. To examine possible relationships between NJC, average movement angular velocity and movement direction and amplitudes we used a linear mixed factor model with the participants as random factor. Since a scatter plot of the average angular velocity and NJC displayed a curvilinear relationship, while a log–log plot showed an approximate linear relationship (see Appendix, Fig. A.1), log-transforms were used in the analyses. Pearson’s correlation coefficient was used to explore a possible relationship between age and the main outcome variables for all small amplitude movements at the P speed condition. This test was also used to examine a relationship between NJC and the number of submovements across the four small amplitude movements. Paired *t*-tests were used to test for differences in the outcome variables when comparing 4% and 10% of the peak velocity as threshold value for movement onset and offset. To test for reliability of our main outcome variables, we calculated the intraclass correlation coefficient (ICC) model 1,1 (Shrout & Fleiss, 1979) and the coefficient of variation (CV). CV was calculated as the within-subject standard deviation divided by the pooled mean across tests and multiplied by 100. Tests are two-sided and p-values less than .05 were considered statistically significant. Statistical analyses were performed using the SPSS 18 and JMP 9.0 statistical packages.

3. Results

3.1. Reliability

The reliability of our main outcome variables is shown in Table A.1 (Appendix). In general, the ICC values for duration, displacement and peak and mean angular velocity were acceptable for all movement directions and amplitudes (median value .83; range .66–.95), while the ICC for NJC was more variable, ranging from .33 to .96 (median .69). While the CV was low for duration, displacement and peak and average angular velocity (median value 11.7%; range 5.6–21.5%), the variation was somewhat greater for NJC (median value 31.9; range 13.8–39.8%).

3.2. Duration, displacement and angular velocity

We found no significant systematic effect of age (range 23–51 years) upon movement duration, displacement, peak and average angular velocity, number of submovements or NJC for the P speed condition in any of the four small amplitude movements. Table 1 shows the data for movement duration, displacement and peak and average angular velocity for the three different speed conditions at each of the six different movements. Movement displacement did not differ significantly between the three speed conditions during EFN, FBN, EF and FF, while the displacement during M speed condition differed statistically significantly from that during P and S speed conditions in the FFN and EBN movements (all $p < .01$). Relative to that of the P speed condition, the average angular velocity of the M speed condition was some 3.4 times higher (range 3.0–3.6) while the S speed condition was .4 times lower (range .36–.44) for the four small amplitude movements. The corresponding pooled relative angular velocity values for the M and S speed conditions for the large amplitude movements were

Table 1

Average kinematic data (±SD) for the three speed conditions at each of the six different movements. Significant differences from the P speed condition; ***, $p < .001$; **, $p < .01$.

Movement		Test	Duration (s)	Displacement (°)	Peak velocity (°/s)	Average velocity (°/s)
EFN	($n = 26$)	S	3.72 ± 1.27***	56.8 ± 14.5	31.9 ± 14.6***	17.3 ± 7.3***
		P	1.47 ± .57	55.9 ± 15.3	78.7 ± 26.6	41.4 ± 12.9
		M	.47 ± .14***	57.3 ± 14.5	249.1 ± 66.9***	133.4 ± 48.7***
FBN	($n = 26$)	S	3.62 ± 1.27***	62.4 ± 16.3	39.1 ± 18.5***	20.1 ± 9.5***
		P	1.37 ± .48	60.8 ± 17.2	91.6 ± 26.0	47.0 ± 13.4
		M	.50 ± .17***	63.4 ± 14.3	265.5 ± 69.0***	135.6 ± 41.0***
FFN	($n = 26$)	S	3.74 ± 1.50***	49.6 ± 7.4	30.5 ± 13.2***	15.6 ± 7.1***
		P	1.17 ± .41	48.9 ± 9.4	88.6 ± 30.6	46.0 ± 15.7
		M	.39 ± .09***	55.5 ± 10.9**	278.8 ± 76.5***	148.7 ± 43.9***
EBN	($n = 26$)	S	3.35 ± 1.28***	53.4 ± 8.0	32.0 ± 13.6***	18.5 ± 7.7***
		P	1.28 ± .29	51.4 ± 11.2	88.0 ± 33.7	42.9 ± 15.5
		M	.43 ± .10***	60.0 ± 12.8***	292.7 ± 81.8***	144.1 ± 41.3***
EF	($n = 12$)	S	6.42 ± 2.97***	106.0 ± 12.0	36.6 ± 15.6***	20.1 ± 8.4***
		P	1.62 ± .50	108.5 ± 12.6	141.8 ± 49.3	74.1 ± 26.1
		M	.54 ± .16***	115.2 ± 15.9	429.6 ± 93.5***	228.4 ± 70.4***
FF	($n = 12$)	S	6.16 ± 2.63***	106.7 ± 12.7	38.4 ± 16.9***	20.5 ± 8.6***
		P	1.48 ± .44	107.5 ± 12.1	144.2 ± 43.8	78.7 ± 23.1
		M	.56 ± .19***	114.5 ± 17.1	410.8 ± 115.4***	221.3 ± 71.4***

Abbreviations: NP – neutral head position, EFN – extension from NP, FBN – flexion back to NP, FFN – flexion from NP, EBN – extension back to NP, EF – full extension, FF – full flexion, S – slow movement speed, P – preferred movement speed, M – maximum movement speed.

3.1 and .3, respectively. While the average angular velocity at the M and P speed conditions were 1.6 and 1.7 times greater for the large ($n = 12$) versus the small ($n = 26$) amplitude movements pooled, respectively, the S speed condition was performed at equal average angular velocity for the two different movement amplitudes.

3.3. Movement smoothness

The NJC differed between velocities for all movements (Table 2). The P and M speed conditions displayed relatively low NJC values and were of similar magnitude irrespective of movement direction or amplitude, thus representing smooth movements. In contrast, the S test expressed large NJC values across all six movements. As shown in Fig. 2, the angular velocity profiles, taken from a representative participant, was also clearly different between test speeds. While the M- and many of the P speed conditions were relatively unimodal in the angular velocity profile shape, the S speed condition typically displayed multiple velocity peaks, indicating the increase in the number of submovements by reduced speed condition across all movements (Table 2). We also found a strong positive correlation between NJC and number of submovements for the four small amplitude movements pooled ($r = .93$). About 90% of the trials were completed using only 1 submovement at the M speed condition. For the P speed, about 37% of the trials was completed by 1 submovement for the small amplitude case and 17% for the large amplitude movements. None of the trials at the S speed condition for any movement condition were completed by one submovement only. Consequently, some of the trials at the M and the P speed conditions were more irregular (Fig. 3). There was a general tendency for the large amplitude movements to be more irregular than the short amplitude movements, both measured as NJC and number of submovements.

3.4. Relationship between movement angular velocity and smoothness

As illustrated in Figs. 4 and 5A, we found a strong effect of movement angular velocity on overall movement smoothness as assessed by the NJC. This was true for all movement directions and amplitudes (all $p < .0001$). When comparing the four small – with the two large amplitude movements, the

Table 2
Normalized jerk cost (a.u.) and number of submovements for the three speed conditions at each of the six movements. Results are mean ± SD. Significant differences from the P speed test; ***, $p < .001$; **, $p < .01$; *, $p < .05$.

Movement		Test	NJC (a.u.)	Submovements (no.)
EFN	($n = 26$)	S	$407.4 \pm 329.6^{***}$	$10.5 \pm 5.6^{***}$
		P	53.8 ± 36.5	2.2 ± 1.4
		M	$32.0 \pm 20.6^{*}$	$1.2 \pm .4^{**}$
FBN	($n = 26$)	S	$413.7 \pm 339.2^{***}$	$10.5 \pm 6.0^{***}$
		P	45.2 ± 28.2	$1.6 \pm .9$
		M	$21.4 \pm 8.5^{***}$	$1.0 \pm .1^{**}$
FFN	($n = 26$)	S	$534.5 \pm 528.1^{***}$	$12.1 \pm 7.3^{***}$
		P	39.3 ± 24.8	$1.7 \pm .8$
		M	$17.7 \pm 8.6^{***}$	$1.0 \pm .1^{**}$
EBN	($n = 26$)	S	$327.7 \pm 325.8^{***}$	$10.4 \pm 7.6^{***}$
		P	43.8 ± 18.0	$1.4 \pm .5$
		M	$22.9 \pm 6.2^{***}$	$1.0 \pm .1^{**}$
EF	($n = 12$)	S	$1225.1 \pm 1316.8^{*}$	$21.3 \pm 14.2^{**}$
		P	52.4 ± 22.1	$2.0 \pm .6$
		M	$23.7 \pm 16.2^{**}$	$1.1 \pm .3^{**}$
FF	($n = 12$)	S	$1193.2 \pm 1240.4^{*}$	$19.6 \pm 11.8^{**}$
		P	45.8 ± 22.2	$1.9 \pm .9$
		M	$19.4 \pm 9.6^{**}$	$1.1 \pm .3^{*}$

Abbreviations: NP – neutral head position, EFN – extension from NP, FBN – flexion back to NP, FFN – flexion from NP, EBN – extension back to NP, EF – full extension, FF – full flexion. S – slow movement speed, P – preferred movement speed, M – maximum movement speed.

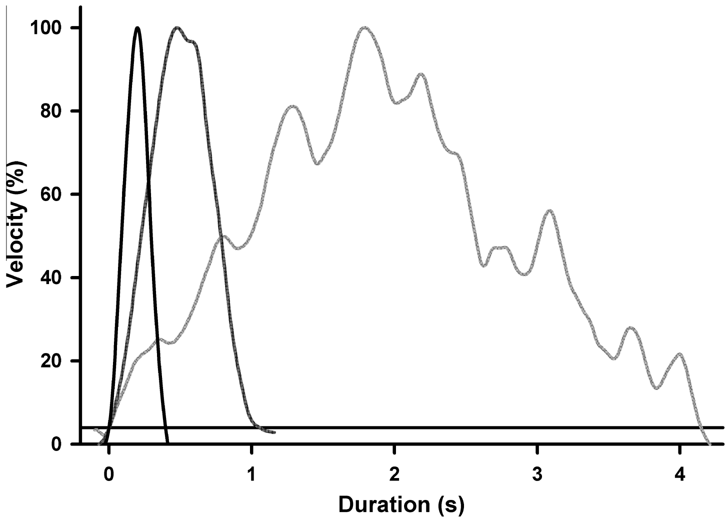

Fig. 2. Example of normalized velocity versus absolute time for the three speed conditions (M; black line, P; dark grey line, S; light grey line) from one subject for the flexion from neutral position movement. The subject scored approximately median values for all speed conditions. Solid horizontal line depicts the relative value of peak velocity defining movement onset and offset (4%).

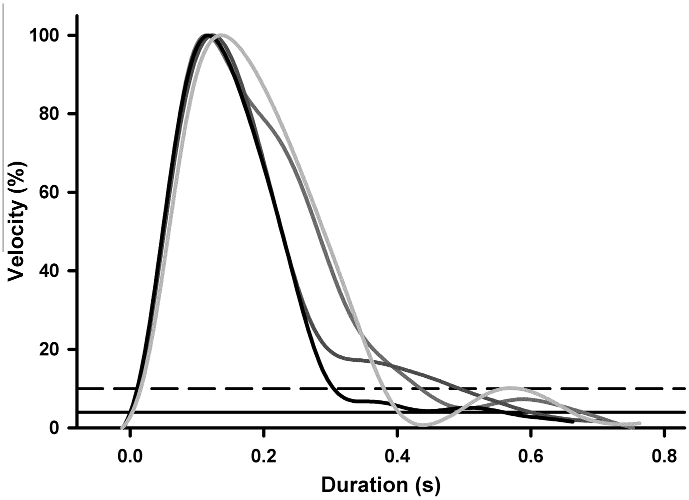

Fig. 3. Examples of non-smooth movements at the M speed condition for the extension from neutral position of 4 subjects. The velocity profiles (different shades of grey) represent separate trials and subjects. Horizontal line corresponds to the relative value of peak velocity defining movement onset and offset (4%). Dashed line represents 10% of peak velocity. Velocity is normalized (%) and time absolute (s).

large amplitude movements display higher NJC values for a given average angular velocity ($p < .001$, Fig. 5A). We also found a small, but statistically significant difference between the four small amplitude movements; the EFN displayed higher NJC for a given angular velocity than the other small amplitude movements ($p < .05$).

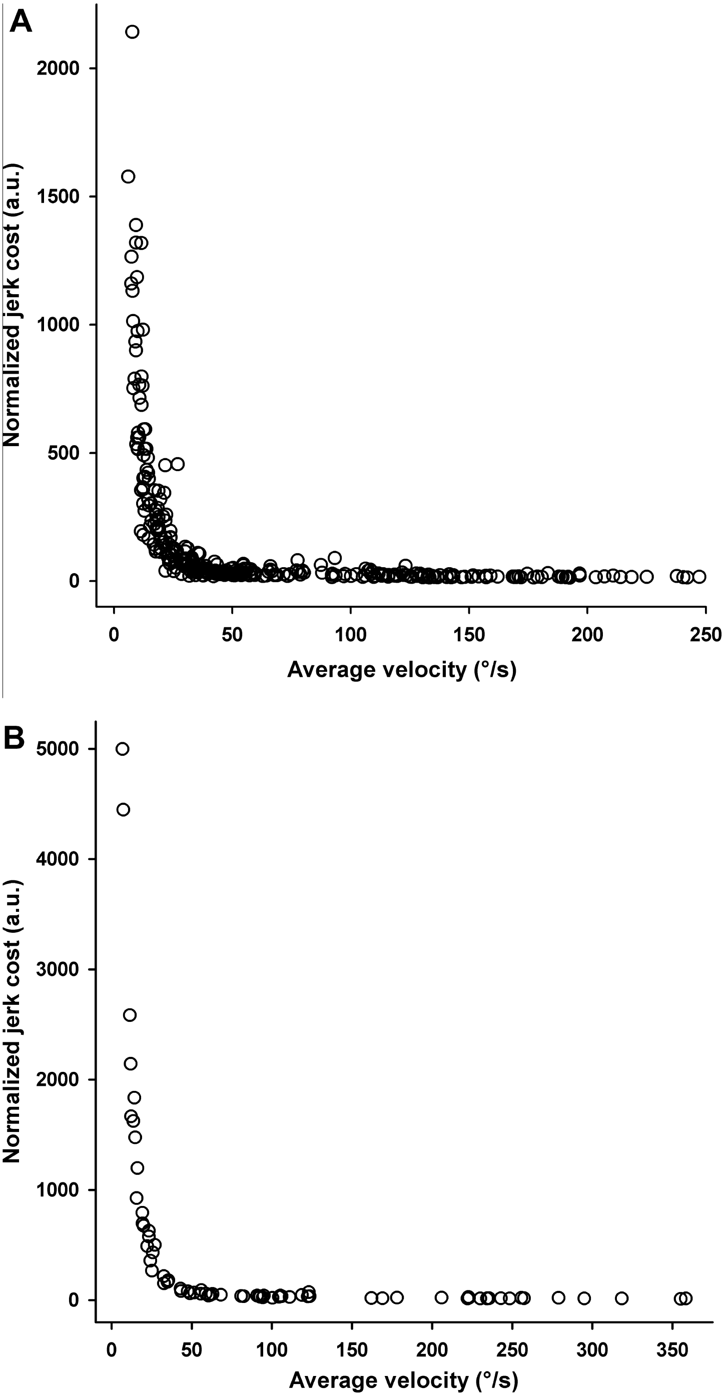

Fig. 4. Relationship between normalized jerk cost (a.u.) and average velocity (°/s) across all speed conditions for the four small (n = 26) and two large amplitude movements (n = 12). Small amplitude movement consists of 312 separate trials and large amplitude movements 72 trials.

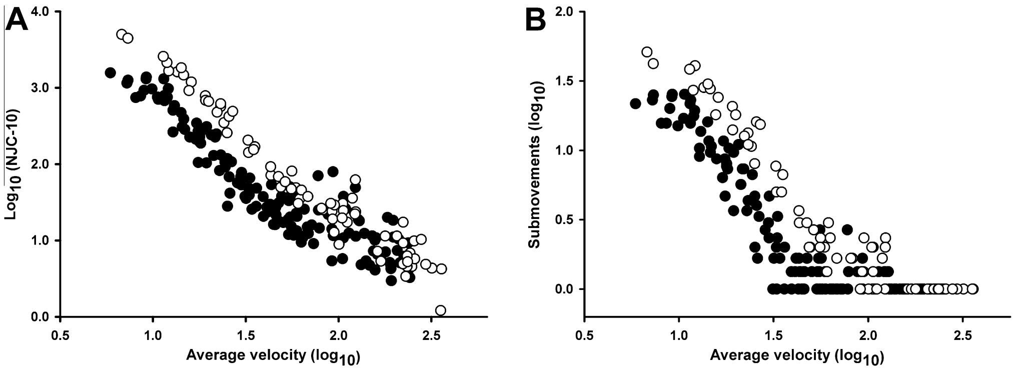

Fig. 5. Log-log plots for average velocity versus A; NJC(-10) and B; number of submovements, for all speed conditions in four small amplitude movements pooled (filled circles, 144 trials) and two large amplitude movements pooled (open circles, 72 trials) in 12 subjects.

3.5. Movement threshold

With the exception of peak velocity, there were significant differences between the 4% and 10% of peak velocity thresholds for the movement onset and offset on all kinematic outcome variables, although the numerical differences were moderate (see Appendix Table B.1 for detailed results). The relationship between movement smoothness and movement velocity was found using both thresholds (Appendix Fig. B.1).

4. Discussion

The main finding in this study was that the smoothness of unconstrained voluntary head movements in healthy humans is strongly dependent on the movement angular velocity. This relationship was found for all movement directions and amplitudes. However, the two large amplitude movements displayed higher NJC values for a given angular velocity than small amplitude movements.

4.1. Are slower movements less smooth than faster ones?

Everyday movements, such as walking, reaching and pointing appear to be executed smoothly when the precision demands of the movements are limited. When such movements are time- and velocity normalized, the velocity profiles typically display approximately symmetrical bell-shaped forms and are reported to be invariant over a threefold increase in movement velocity (Atkeson & Hollerbach, 1985). In line with this, we observed unimodal velocity profiles containing a single submovement over a relatively large range in angular velocity. However, the frequency of unimodal velocity profiles was gradually reduced as the velocity of movement decreased and the main finding was that the overall smoothness of head movements was strongly dependent upon the movement angular velocity and this relationship was observed for all head movement directions and amplitudes examined (Fig. 4). Examples of representative individual velocity profiles for the three different speed conditions are illustrated in Fig. 2. As seen from this figure, there is a clear difference in the velocity profiles between the three speed conditions, which is a visual representation of the statistical difference in both NJC values and the number of submovements between speed conditions (Table 2). The velocity profile of the S speed trials (Fig. 2) are very similar to the profiles described previously in slow, moderately constrained arm and finger movements in healthy participants (Darling et al., 1988; Milner, 1992; Milner & Ijaz, 1990; Morasso et al., 1983). Our findings are therefore in line with their observations. Similar findings have also been reported for spatio-temporal constrained movements. van der Wel et al. (2009) found that repetitive, back and forth slower arm movements displayed statistically significant more submovements than faster movements. Our findings extend these results to unconstrained head movements, indicating that slower movements are less smooth than faster movements over a wide range of movement situations and anatomical regions.

Even though there is a strong association between speed and smoothness, both NJC and submovements show some variation at a given speed. The moderate reliability for NJC at preferred speed underscores this finding, although there was also some variation in velocity in the test–retest. It seems likely that difference in movement displacement may generate some of this variation in smoothness since we found an effect of movement displacement upon movement smoothness at a given velocity. However, it is also possible that an underlying, true individual difference in movement smoothness explains parts of this variation in NJC and submovements at a given velocity.

4.2. Why are slower movements less smooth than faster ones?

For a chosen set of data consisting of movements of about 55° displacement, we observed unimodal velocity profiles for velocities ranging from 203°/s (261 ms) to 31°/s (1763 ms), which suggests that a single submovement could be scaled in terms of a velocity and time factor above 6 to cover a given movement. Lower velocities movements were all completed with additional submovements. This is in line with the results of Milner and Ijaz (1990), who reported that for deliberately prolonged pointing movements from about 380 ms to about 1000, irregularities appeared in the velocity profile, thus which they suggested to be a series of overlapping submovements. Therefore it seems to be a lower limit for which a single submovement can be scaled to cover a given movement. Milner and Ijaz (1990) proposed the hypothesis that the appearance of submovements were related to the regulation of movement duration. They speculated whether single motor commands of long duration was difficult to generate and that movements of long duration was approximated by an overlapping sequence of submovements at shorter intervals. Our results may strengthen the hypothesis proposed by Milner and Ijaz (1990) since in addition to movement speed we also examined different amplitudes. We found the trials with the longest duration that were composed of a single submovement had similar movement duration for both movement amplitudes (1763 ms for the small amplitude- and 1860 ms for the large amplitude movements). Thus, an approximate doubling of the movement amplitude did not increase the total movement time for a movement consisting of a single submovement. Our findings suggest that unconstrained movements at the middle and faster end of the speed continuum are mostly accomplished by temporal scaling of a single submovement to cover the movement, which is in accordance with previous studies. At the slower end of the speed continuum, a single submovement cannot longer scale to cover the movement but is completed by additional submovements. Such repetitive submovements have been suggested to be of central origin. Vallbo and Wessberg (1993) demonstrated that for slow tracking movements of the finger, velocity peaks was reoccurring at about 8–10 Hz. Furthermore, they found these submovements to be driven by pulsative gross muscle activation patterns of both the agonist and antagonist muscles. The single motor unit activity and acceleration signal of both finger and wrist movements display coherence (Kakuda, Nagaoka, & Wessberg, 1999; Wessberg & Kakuda, 1999) and pairs of motor units correlate (Kakuda et al., 1999) around these frequencies, which are pointing towards a common modulation of motor unit activity. A common modulator of motor unit firing during slow finger movement has been identified in the sensimotor cortex both in humans and monkeys (Gross et al., 2002; Williams, Soteropoulos, & Baker, 2009) and is regulated by synchronized, oscillatory activity in the cerebello–thalamo–cortical loop (Gross et al., 2002). This firm connection between cerebral neural activity, muscle activity and movement imply that passive mechanical factors do not play a central role in the origin of submovements. However, as we have no data quantifying either central or peripheral activation patterns, we cannot confirm such a hypothesis although it fits well with the pulsatile behavior of the velocity tracings during slow movements in the present study.

4.3. Effect of movement amplitude

The large amplitude movements displayed higher NJC values for a given average angular velocity than the small amplitude movements (Fig. 5A). This was somewhat unexpected, since NJC is normalized for duration and displacements and thus movements completed by a single submovement should display similar NJC values, irrespective of movement velocity. However, when comparing the trials composed of one single submovement for the M speed condition, the small and large amplitude movements did display almost identical NJC-values despite a large difference in both displacement and angular velocity, thus they were equally smooth. Since the M and P speed conditions were completed at substantially greater average movement angular velocity at the large amplitude movements than the small amplitude movements, this implies that the large amplitude movements are jerkier than small amplitude movements when comparing equal angular velocities. The clear difference in NJC between the two movement amplitudes appears when they are exerted equally fast at the low angular velocity continuum (S speed condition; Fig. 5A). For the S speed condition, both movement amplitudes were completed at comparable angular velocities, but the large amplitude movements displayed far higher NJC-values and approximately twice the number of submovements compared to the small amplitude movements. Thus, if the movement amplitude is increased while movement velocity is unchanged, the number of submovements necessary to complete the movement is increased.

4.4. The effect of threshold for movement onset and offset

We conducted a comparative analysis of threshold values of 4% and 10% of peak velocity for the EFN movement and found moderate numerical effects on the kinematic variables in general. However, some trials of the M speed condition were composed of several submovements when analyzed using the 4% threshold and for some of these trials the additional submovements were removed when using the 10% threshold, since they appeared at low velocity towards the end range of the movement (Fig. 3). Consequently, the choice of threshold had a relatively large impact upon the kinematic variables for these given trials. We therefore chose to use the 4% threshold in the present study since it included a larger part of these movements and not only the smoother part. However, for the main topic of this study, the choice of threshold did not appear to be critical, since the relationship between movement angular velocity and movement smoothness was identified using either threshold (Fig. B.1).

4.5. Implications

Previous studies have reported differences in the smoothness of movement between various groups of participants. Arm movements in children and senior adults are shown to be less smooth than compared to young adults (Ketcham et al., 2002; Poston, van Gemmert, Barduson, & Stelmach, 2009; Yan, Thomas, Stelmach, & Thomas, 2000) and head movements in musculoskeletal neck pain are less smooth than compared with healthy controls (Grip et al., 2008; Sarig Bahat et al., 2010; Sjölander et al., 2008), implying altered motor control patterns. In several of these studies, the speed of movement also differed between the compared groups (Grip et al., 2008; Ketcham et al., 2002; Poston et al., 2009; Sarig Bahat et al., 2010; Yan et al., 2000). However, these studies did not examine whether the exerted speed and the smoothness of the movement were related. It is therefore possible that movement smoothness is not only affected by age or pain per se, but may in addition be an accompanying result of differences in movement speed and amplitude. Hence, the present findings might have implications for how to assess and compare movement smoothness both in unimpaired humans and in clinical studies. Both the velocity and displacement of the movement should be taken into consideration when designing and interpreting studies comparing movement smoothness of different age groups or populations.

5. Conclusions

We have shown that the smoothness of head movements is strongly related to the movement velocity, thus fast movements are smooth while slow movements are jerky. In addition, movements of larger amplitude are less smooth than movements of smaller amplitude.

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Appendix A

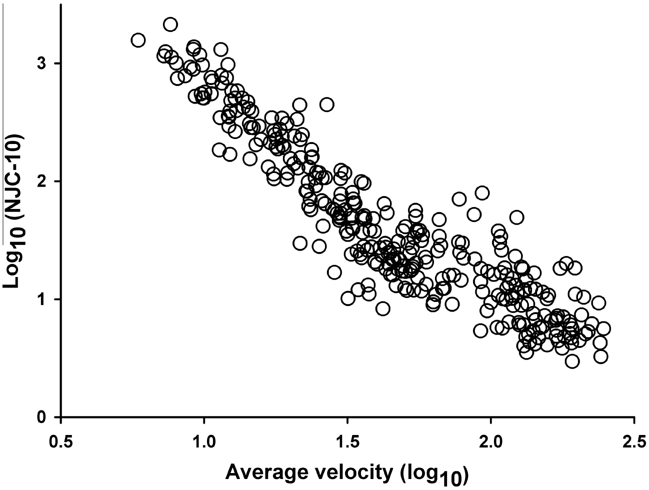

Fig. A.1. Relationship between average velocity ($\log_{10}$) and NJC(-10) ($\log_{10}$) across all speed conditions for all small amplitude movements pooled (26 subjects, 312 trials).

Table A.1
Test–retest reliability of the main outcome variables for all movement directions for the P speed condition ($n = 12$). Reliability is measured by the intraclass correlation coefficient (ICC1,1) with 95% CI and coefficient of variation (CV).

Direction		Duration	Displacement	Peak velocity	Mean velocity	Norm. Jerk Cost
EFN	ICC	.87 (.63–.96)	.81 (.47–.94)	.66 (.18–.89)	.63 (.14–.88)	.72 (.30–.91)
	CV	16.0	7.7	20.8	21.5	39.8
FBN	ICC	.95 (.83–.98)	.69 (.25–.90)	.66 (.20–.89)	.71 (.28–.91)	.96 (.88–.99)
	CV	9.5	9.1	15.8	15.8	13.8
FFN	ICC	.78 (.41–.93)	.88 (.64–.96)	.88 (.64–.96)	.90 (.70–.97)	.33 (−.25–.75)
	CV	14.1	6.4	11.6	11.3	38.4
EBN	ICC	.68 (.22–.89)	.90 (.71–.97)	.89 (.67–.97)	.82 (.51–.94)	.42 (−.15–.79)
	CV	15.0	6.0	11.8	15.0	34.6
EF	ICC	.80 (.46–.94)	.75 (.35–.92)	.84 (.55–.95)	.83 (.54–.95)	.66 (.18–.89)
	CV	15.0	6.3	14.2	13.9	29.1
FF	ICC	.90 (.70–.97)	.78 (.42–.93)	.87 (.64–.96)	.91 (.73–.97)	.78 (.42–.93)
	CV	10.8	5.6	11.1	9.3	28.9

Abbreviations: NP – neutral head position, EFN – extension from NP, FBN – flexion back to NP, FFN – flexion from NP, EBN – extension back to NP, EF – full extension, FF – full flexion.

Appendix B

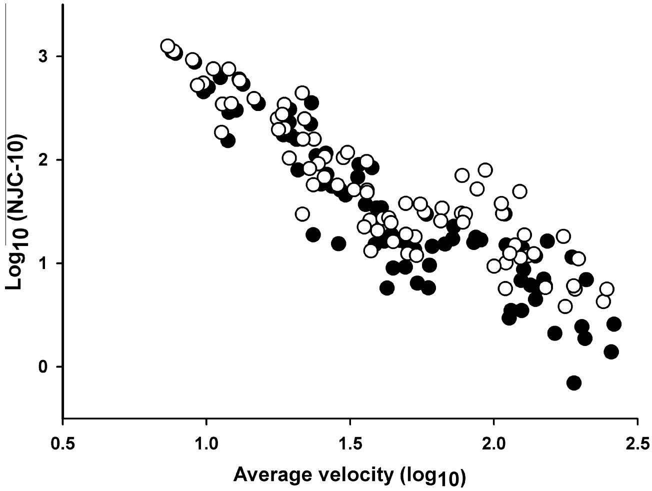

Fig. B.1. Relationship between average velocity ($\log_{10}$) and NJC(-10) ($\log_{10}$) across all speed conditions for the EFN movement at movement threshold values of 4% (open circles) and 10% (filled circles) of the peak velocity (26 subjects, 78 trials at each threshold).

Table B.1

Differences in the main outcome variables for the three different speed conditions at the extension from the neutral position movement using 4% or 10% of peak velocity as threshold for movement onset and offset. Significantly different from the 4% threshold; **, $p < .001$; *, $p < .05$.

Speed	Cutoff (%)	Duration (s)	Displacement (°)	Mean velocity (°/s)	NJC (a.u.)	Submovement (no.)
S	4	3.72 ± 1.27	56.8 ± 14.5	17.3 ± 7.3	407.4 ± 329.6	10.5 ± 5.6
	10	3.49 ± 1.26**	56.3 ± 14.3**	18.5 ± 8.2**	354.1 ± 306**	10.0 ± 5.5**
P	4	1.47 ± .57	55.9 ± 15.3	41.4 ± 12.9	53.8 ± 36.5	2.2 ± 1.4
	10	1.31 ± .53**	55.2 ± 15.2**	45.9 ± 14.4**	39.1 ± 28.7**	2.0 ± 1.4*
M	4	.47 ± .14	57.3 ± 14.5	133.4 ± 48.7	32.0 ± 20.6	1.2 ± .4
	10	.39 ± .11**	56.4 ± 14.5**	149.9 ± 47.8**	18.5 ± 7.0**	1.1 ± .1*

Abbreviations: S – slow movement speed, P – preferred movement speed, M – maximum movement speed.

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