Comparison of Various Smoothness Metrics for Upper Limb Movements in Healthy Subjects

Nicolas BAYLE (nicolas.bayle@aphp.fr)
UR 7377 BIOTN, Université Paris Est Créteil (UPEC)

Mathieu LEMPEREUR
U1101 LaTIM, Université de Brest

Emilie HUTIN
UR 7377 BIOTN, Université Paris Est Créteil (UPEC)

Damien MOTAVASSELI
AP-HP, Hôpitaux Universitaires Henri Mondor

Olivier REMY-NERIS
U1101 LaTIM, Université de Brest

Jean-Michel GRACIES
UR 7377 BIOTN, Université Paris Est Créteil (UPEC)

Gwenaël CORNEC
Service de Médecine Physique et de Réadaptation – CHRU de Brest – Brest

Research Article

Keywords: Motion analysis, Kinematics, pointing task

Posted Date: March 16th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1431894/v1

Abstract

Background

Metrics for movement smoothness include the number of zero-crossings on acceleration profiles (N0C), the Log Dimensionless Jerk (LDLJ), the Normalized Averaged Rectified Jerk (NARJ) and the Spectral Arc Length (SPARC). Sensitivity to handedness and movement type of these four metrics were compared and correlations with other kinematic parameters were explored in healthy subjects.

Methods

Thirty-two healthy participants (age 63±16 y) underwent 3D upper limb motion analysis during two sets of pointing movements on each side. Participants were seated, palm of the hand facing down on the table before movement onset; they performed forward-pointing movements (FPM) at self-selected speed to a target located ahead at shoulder height and at 90% arm length, and backward pointing movements (BPM), back to the initial position, with and without a three-second pause between FPM and BPM. Kinematics (including trajectory and velocity) were collected and N0C, SPARC, LDLJ and NARJ were computed.

Results

LDLJ, NARJ and N0C found backward movements to be smoother while SPARC found the opposite. No smoothness metric indicated differences across sides. Inter- and intra-subject coefficients of variation were lowest for SPARC. LDLJ, NARJ and N0C were correlated with each other and with movement time, unlike SPARC.

Conclusions

There are major differences between smoothness metrics measured in the temporal domain (N0C, LDLJ, NARJ), which depend on movement time, and that measured in the frequency domain, the SPARC, which gave results opposite to the other metrics when comparing backward and forward movements.

Trial Registration

Registration number, ID-RCB: NCT01383512, registered on 28 June 2011, updated on 11 October 2017.

Approved by the Institutional Review Board of Brest University Hospital under the number 653.

Introduction

Quantitative assessment of upper limb mobility[1,2,3] often uses clinical (using manual goniometry) or instrumented (using accelerometers, electronic goniometers, or 3D motion analysis tools) evaluation of segmental displacements (passive and active range of motion).[4] These assessments, basically based on position, velocity and acceleration calculation, may lack sensitivity to detect small changes in movement trajectories and velocities in slowly progressive disorders like spastic paresis syndromes or parkinsonism.[2] They may be inadequate to differentiate between various types of movement slowness (bradykinesia) induced by the many kinds of neurological, orthopaedics and psychological disorders (as parkinsonian bradykinesia and voluntary or drug-induced bradykinesia)[5,6] or to demonstrate changes after rehabilitation programs or injections of blocking agents in chronic neurological disorders.[7]

In healthy individuals, most discrete reach-to-point movements use a single acceleration burst per movement, making the resulting movement "smooth" with a bell-shaped velocity profile; these movements may be modelled as successions of sub-movements closely overlapping at each instant.[8–10] Most human motor disorders, by introducing irregularities in the trajectories and velocity profiles, make the resulting movements less smooth, with more movement interruptions.[10,11] Thus, movement smoothness metrics may represent an alternative to the classic clinical tools to better assess small changes in movement kinematic properties.[12] A number of mathematical metrics to quantify smoothness have been suggested over time.[12–14] Some of those metrics are based on the observation of changes in kinematic properties of movements such as changes in movement trajectories, changes in the velocity profile or assessments of the rates of changes in the acceleration profile (jerk-derived metrics).[9–11, 14] Those metrics of smoothness can be categorised as using the "*temporal domain*", and have been criticized as having shortcomings such as strong sensitivity to measurement noise and direct dependence to other kinematic parameters (movement amplitude and duration), lack of reliability and poor robustness.[12,13] Other smoothness metrics based on the detection of changes in frequencies of movement components have been more recently developed, considering than smooth movements mainly contain low frequency components, in contrast with unsmooth movements which may be contaminated by high frequency components.[12,13] Among the latter metrics, the spectral arc length measure (SPARC), quantifies the complexity of the Fourier magnitude spectrum of the velocity profile; it can be categorised using the "*frequency domain*".[12,13]

Comparisons of these various smoothness metrics across clinical protocols are difficult.[6,15] Validations and comparisons of these metrics have been mostly performed on simulated movements.[12,13] In a recent study, Refai et al. (2021) assessed 32 smoothness metrics used in stroke patients with mathematical criteria to be accepted as smoothness measures (metrics had to be dimensionless, reproducible, based on rate of change of position, and not being a linear transform of other smoothness metrics), then tested them for their response to simulated changes in reaching.[16] They ended up recommending SPARC as a valid smoothness metric in both reach-to-point and reach-to-grasp tasks of the upper limb after stroke.

It thus appears that a normative basis for the main smoothness metrics for upper limb (UL) movements of interest is required, not based on simulations but on actual human data (i.e., movements commonly used in neuro-rehabilitation programs to assess changes, such as forward or side-wise pointing movements), acquired from healthy participants, to better interpret future patient data. This study aimed to build normative values and compare the properties of the SPARC, the Normalised Average Rectified

Jerk (NARJ), the Log Dimensionless Jerk (LDLJ) and the number of zero-crossings in the acceleration profile (N0C) for point-to-reach movements in healthy subjects.

Methods

This prospective study was conducted in accordance with the Declaration of Helsinki (2008), Good Clinical Practice guidelines and local regulatory requirements (registration number, ID-RCB: NCT01383512). It was approved by the Brest University Hospital IRB (n°653). All subjects gave written consent to the inclusion of material pertaining to them. All the experimental sessions were conducted in December 2019 in the Laboratory of Movement Analysis of Brest University Hospital (Brest, France). We recruited thirty-two healthy participants (18 males, 29 right-handed, aged 63 ± 16 years [21–79]), with no history of neurological, orthopaedic, rheumatologic, neuromuscular or visual disorders nor impairment of the mobility of their upper limb, to participate in a research study on human movement. Prior to the movement analysis, every participant underwent a clinical assessment of both upper limbs to verify that active ranges of motion for both shoulders, elbows, wrists and finger joints were full and pain free.

Experimental Set-up

All participants underwent a 3D upper limb motion analysis while performing two sets (A and B) of three point-to-point movements with each UL. Participants were comfortably seated in a chair; in the starting position, they had the elbow flexed at 90 degrees resting on the table, the palm of their hand facing down on the table. The point-to-point movement consisted of reaching a target located in front at 90% of upper limb length (forward pointing movement, FPM) and bringing the hand back to the baseline position (backward pointing movement, BPM), all of it at comfortable speed. In set A, participants were asked to mark a short pause between FPM and BPM (not exceeding three seconds), while in set B, participants proceeded to BPM directly after FPM. The paradigm was chosen to test the effect of the transition between the forward and the backward movement on movement smoothness. Each full point-to-point movement was repeated four times, the first attempt being considered as a training movement and thus not recorded. These two sets of movements were completed consecutively with the dominant and the non-dominant UL. Combining these conditions, a total of 768 movements (24 movements per subject) were recorded and analysed.

Upper limb movements were recorded using a 15-camera 100Hz sampling Vicon motion capture system (Oxford Metrics, Oxford, UK). Reflective markers (14mm) were placed on classical UL anatomical landmarks: the mid-hand marker was positioned on the third metacarpal on the back of each hand. Supplementary markers were positioned on the head of the olecranon, head of second and fifth metacarpal and styloid processes of the radius to detect potential artefacts and ensure visual consistency. The same investigator placed all markers at each session.

Data analysis

Analyses focused on the mid-hand marker (placed on the third metacarpal, on the back of the hand). A 6-Hz second order low-pass Butterworth filter was applied to the trajectories before analyses. Each recorded trajectory was visually inspected twice by the same investigator to manually define the beginning and end of each movement. The start of the FPM was the first ascending point of the projection of the trajectory in the vertical direction; the end of the FPM, which was also the start of the BPM, was the outermost point of the trajectory in the postero-anterior direction. The end of the BPM was the last point of the descending trajectory in the vertical direction, just before the rebound of the hand on the table.

All outcomes were calculated on Python software as the mean value of the three recorded movements in each set. First, second, and third derivatives of trajectory of the mid-hand marker data were calculated across all three plans of space to retrieve the velocity, acceleration, and jerk profiles. The index of curvature (IoC) was computed and defined as the ratio of the arc length of the trajectory to the length of the straight line linking the first and the last movement points, as a straightness measure.

Smoothness was quantified using three temporal domain metrics (NARJ, LDLJ and N0C) and a frequency domain metric (SPARC).

The NARJ is the normalised version of the Average Rectified Jerk (ARJ) previously described by Cozens and Bhakta.[14] Considering a movement of total duration T, with a trajectory for the x^{th} degree of freedom represented by trajectory = x(t) where $0 \leq t \leq T$, then the ARJ for the x^{th} degree of freedom for this movement is given by the formula $\frac{1}{T}\int_0^T \left|\frac{d^3x(t)}{dt^3}\right| dt$. The ARJ is thus highly dependent on movement duration, with a longer movement yielding a higher ARJ than a movement of identical shape but shorter duration. The NARJ was then calculated by multiplying the ARJ by a normalization factor $[(T'/T)^3]$ allowing the comparison of smoothness among a group of movements with the same trajectory but different durations (T’) which was, within a given series, the cube of the ratio of the average control movement frequency to that of the subject under analysis. As the Jerk reflects the rate of change in the acceleration profile, an increased NARJ magnitude reflects decreased smoothness (more frequent changes in acceleration).

The LDLJ results from the logarithm naturalis of the sum of the squared acceleration multiplied with the trial duration to the power of three and divided by the squared peak velocity.

$$\mathrm{DLJ} \triangleq -\frac{(t_2 - t_1)^5}{v_{peak}^2} \int_{t_1}^{t_2} \left|\frac{d^2 v(t)}{dt^2}\right|^2 dt$$

$$\mathrm{LDLJ} \triangleq -\ln|\mathrm{DLJ}|$$

Calculation of the LDLJ is based on the velocity profile *v* within the time window t1 to t2. The LDLJ was designed to fix one major shortcoming of jerk-metrics, direct dependence to movement amplitude and duration.

The SPARC was computed from the arc length of the power spectrum of a Fourier transformation of the velocity signal, with [0, ωc] being the frequency band and V(ω) the Fourier Magnitude spectrum, as defined by Balasubramanian.[12]

$$\mathrm{SAL} \triangleq -\int_0^{\omega_c} \left[\left(\frac{1}{\omega_c}\right)^2 + \left(\frac{d\hat{V}(\omega)}{d\omega}\right)^2\right]^{\frac{1}{2}} d\omega; \quad \hat{V}(\omega) = \frac{V(\omega)}{V(0)} \qquad \omega_c \triangleq \min\left\{\omega_c^{max}, \min\left\{\omega \ , \hat{V}(r) < \overline{V} \ \forall \ r > \omega\right\}\right\}$$

As recommended by Balasubramanian et al. (2015), our choice for $\overline{V}$ was 0.05, with 20Hz for ω_c^{max}.

The SPARC and the LDLJ were computed using the Python code provided by Balasubramanian et al.,[12] in which we added the computation of the NARJ[14] and the N0C (equal to 1 in a movement considered as smooth).

Statistics

Descriptive statistics were performed to provide average values with standard deviations. Coefficients of variation (CoV - defined as the standard deviation divided by the mean value; used to evaluate data dispersion) were calculated between tries (CoV_{intra}) and between subjects (CoV_{inter}) to estimate within- and between-subject variability respectively. Normality of data was assessed using Shapiro-Wilk tests, and parametrical or non-parametrical tests for comparison were used accordingly. For each outcome, dominant and non-dominant sides, FPM and BPM, and sets A and B were compared. Construct validity was evaluated using correlations between smoothness metrics (convergent validity) and with movement duration (divergent validity). All statistical analyses were performed using SPSS 20 (IBM, Armonk, NY).

Results

A total of 768 movements (24 movements per subject) were analysed. There was no missing data.

Usual kinematic parameters

All results of the 4 usual kinematic parameters - movement duration, index of curvature, peak speed and mean speed - are presented in Table 1. In set B (without pause), both movement types were shorter in duration, straighter and faster with a higher mean and peak speed compared to set A (with pause). In both sets, BPM were shorter in duration, faster with a higher mean speed but not straighter. Notably, there was no systematic difference between sides except for the IoC, with straighter movements on the dominant side. More variability was observed across subjects than across repetitions.

Smoothness parameters

All results of the 4 smoothness parameters - N0C, NARJ, LDLJ and SPARC - are presented in Table 2 and Fig. 1. According to the temporal domain smoothness metrics (TDSM, including N0C, NARJ and LDLJ), BPM were smoother than FPM. According to the SPARC, they were less smooth. TDSM found movements without pause to be smoother while SPARC did not find changes in smoothness between the two sets of movements. No metric indicated differences across sides (dominant/non-dominant). Inter- and intra-subject coefficients of variation were lowest for the SPARC.

Correlations

The analysis of correlation usual kinematic parameters and smoothness parameters is illustrated in Fig. 2. The three TDSM were strongly correlated together and to movement duration. SPARC was not correlated to TDSM, nor to movement duration. Smoothness metrics were not correlated to age or sex.

Discussion

This study reports for the first time, at our knowledge, the comparison of the main smoothness measures from both temporal and frequency domains on different sets (with or without pause) and types of actual point-to-point movements (forward and backward) in healthy subjects. The 4 smoothness parameters, N0C, NARJ, LDLC and SPARC, were sensitive to movement type, but the SPARC behaved differently than the temporal domain smoothness metrics (TDSM), finding backward movements to be less smooth than forward movements instead of the opposite. Only the TDSM were sensitive to movement set. TDSM strongly correlated with movement duration, whereas the SPARC did not. Within-subject repeatability was highest and between-subject variability was lowest for the SPARC. No difference in movement velocity nor smoothness was found across sides but movements were slightly straighter with the dominant arm. A normative dataset was built for each metric and is now available.

Different behavior between temporal domain smoothness measures and the SPARC- to be or not to be time-connected?

The most striking finding in this study is that temporal domain smoothness measures found backward movements to be smoother than forward movements. In particular there was only about one zero crossing on the acceleration profile in backward movements without pause while the SPARC found backward movements to be less smooth. Except for the fact that backward movements were faster than forward movements (movement time-dependence of metrics measured in the temporal domain), this opposite behavior between the two types of metrics is challenging to interpret.

Interestingly, TDSM were strongly correlated amongst them, while the SPARC was not correlated with any other metrics (low convergent validity) nor to movement duration (strong divergent validity). Besides, TDSM were strongly correlated with movement time. Thus, the changes in smoothness perceived by TDSM across sets (with *vs* without pause) might reflect the sensitivity of those metrics to movement duration. From mathematical models, Balasubramanian suggested shortcomings for temporal domain smoothness measures, including precisely their sensitivity to movement duration (and to noise in measurements) with a risk of lack of reliability and validity.[12] Intellectually though, it may be tempting to speculate that a movement that loses smoothness should also lose speed in the process. It may therefore seem natural that a smoothness metric be somewhat correlated with movement time, at least in pathological or complex movements. Yet, it is also obvious that if no correction means is brought, for instance in adjusting the sampling frequency of the movement recording to movement time, noise is bound to emerge in those metrics that depend on movement time.[5] On the other hand, a metric that involves the frequency domain only may allow bypassing the down-sampling issue and therefore seem more satisfactory. A number of such frequency-domain metrics have been proposed in the literature, for example the determination of the fast frequency to the movement frequency ratio in the acceleration power spectrum (FF/MF ratio), which has provided interesting results when comparing parkinsonian with simulated bradykinesia.[5]

It may be that the temporal domain and the frequency domain smoothness metrics may be irreconcilable. The question as to whether the appropriate smoothness metric should or should not be connected to movement time may come down to the way we wish to *define* smoothness. Perhaps there should be at least two different types of smoothness, depending on whether we connect smoothness to the braking effects of smoothness reduction or not. Future studies comparing those metrics in pathological movements could provide useful insight on their respective behavior and interest.

Coherence of the present smoothness data with previous literature

For forward movements, the present SPARC values (-1.43 to -1.45 ± 0.03) were consistent with recent findings: -1.45 to -1.48 for Engdahl et al. (2016)[18] and − 1.44 ± 0.04 for Saes et al. (2021)[19] in reach to grasp movements. Although themovement type was different in those studies (reach-to-grasp *vs* reach-to-point), the reaching phase was predominant in both types of movement, allowing the comparison. As for LDLJ values, the present data are also consistent with those reported by Engdahl et al. (2019)[17] The N0C values in our findings (3 to 6 ± 3) seem relatively high, as only one zero crossing per movement is expected in healthy and even in some pathologic movements.[18,19] As for the present NARJ values, they were also consistent with previous literature[5] and varied more than twofold (20193 to 46378 ± 17085) depending on the movement type, possibly reflecting both noise and movement duration sensitivity of jerk-related metrics (artefacts in trajectories when movements stopped or during the plateau phase).

Similar observations can be made for backward movements, even though we could not find data in the literature for comparisons. SPARC values were also remarkably consistent across sets (-1.48 ± 0.06), LDLJ shows some differences (-6.64 ± 0.52 to -5.58 ± 0.53), whereas NARJ and N0C values again ranged from single to double depending on the movement type.

Inter- and intra-subject reliability and sensitivity to change of smoothness metrics

Can smoothness characterize one individual’s movement, or can it change between two different movements made by one person? Among the smoothness metrics tested here, SPARC showed the least intra- and between-subject variability for all tested movements (e.g. FPMCoV_{inter} 1.6 to 2.2%) followed by the LDLJ (with higher CoV_{inter}6.8 to 8.7%). On the other hand, the NARJ and N0C were characterized by high levels of inter-subject differences, i.e., High CoV_{inter}. Similarly, the SPARC was characterized by higher intra-subject repeatability (FPM CoV_{intra}1.6 to 1.9%) than TDSM (FPM CoV_{intra} 5.0-6.4% for the LDLJ, 18–30% for the NARJ and 27–40% for the N0C).

In our protocol, each movement was repeated four times, the first attempt being considered as training and thus not retained for computation. We assumed this number of repetitions to be sufficient in healthy subjects for the SPARC computation. Indeed, no differences were observed in the literature when using 7 or 10 repetitions.[20,21] For TDSM, due to their greater variability/sensitivity to changes in movements and/or in movement durations, a higher number of repetitions might have to be used to obtain a reliable mean smoothness value, such as 7–8 movements.[5] This lower number of repetitions needed for the SPARC computation can be interesting in very impaired subjects for whom only fewer movement repetitions may be possible.[21]

Smoothness and laterality - is there an ‘optimal’ smoothness?

If movements on the dominant side were slightly straighter, as previously described,[22] we did not find smoothness differences between sides. Reaching movements are relatively simple, largely used, thus trained, in most daily activities. In more complex tasks like transferring an object with chopsticks, movements have been shown to be longer and less smooth on the non-dominant side, but trainable to become as smooth as on the dominant side.[23] Finally, in healthy subjects, simple movements are expected to be optimally smooth; thus, a ceiling effect should be expected from smoothness measures, as shown in Fig. 3 for the SPARC, the NARJ and the N0C. By applying a logarithmic transformation to normalize the Dimensionless Jerk, the LDLJ displays an artificially normal distribution, which might make interpretations of changes in smoothness more difficult than it is with the other metrics.

Study Limitations

Subjects were asked to complete each task at their preferred speed, and yet found differences in movement durations across movement types and sets, suggesting an explanation for changes in smoothness reported by TDSM. It would have been useful to add sets of movements of various imposed speeds, including ballistic movements at maximal speed, to better explore sensitivity of the four metrics to movement duration.[5]

Reach-to-point movements were tested to aim for normative smoothness data that could be of interest in clinical routine. Pointing movements requiring multi-joint coordination are often used in clinical practice, especially in neurorehabilitation to assess patient progression, as these are simple to assess, reproducible,[24] and frequently used in daily living activities.[25] Moreover, reach-to-point movements are more easily performed than reach-to-grasp movements, especially in numerous neurological disorders that can prevent patients from grasping (stroke, advanced parkinsonism, severe peripheral neuropathies, myopathies…) and have been recommended in more impaired patients.[4] However, smoothness of other movements of interest still needs to be quantified, especially of single-joint movements with the hope of better differentiation between recovery and compensation.[20]

To date, there is no clear consensus on how to determine with precision the onset and the end of a reaching movement. As explained in the Methods section, a single assessor visually inspected each recorded trajectory twice and standardized the beginnings of FPM as the first ascending point of the projection of the trajectory in the vertical direction, and the end of FPM (which also was the beginning of the BPM) as the most forward point of the trajectory in the antero-posterior direction; the end of the BPM being the last point of the descending trajectory in the vertical direction. This method is time-consuming and might have resulted in errors, in contrast with other methods that rely on the detection of changes in maximum tangential speed during the various phases of the movement.[20,25,26] However, those definitions for the starting and ending points of trajectories allow considering more trajectory points at critical stages of movements (such as when nearing the target, where accuracy is needed), with thus perhaps more accurate estimations of smoothness across the whole movement.

Conclusion

This study of actual movements (rather than models), reveals major differences between smoothness metrics measured in the temporal domain (N0C, LDLJ, NARJ), strongly correlated amongst themselves and with movement duration, and the SPARC, derived from the frequency domain. Among smoothness metrics, the SPARC showed less between-subject and within-subject variability for all tested movements and revealed changes between forward and backward movement that were opposite to time-dependent metrics. The present study also helped provide a normative dataset of smoothness measures for reaching upper limb movements in healthy subjects, for each metric, which is available for future studies.

Further studies assessing these measures of smoothness on different movements of interest in upper and lower limbs are needed in healthy subjects, as well as in progressive neurological disorders such as spastic paresis syndromes or parkinsonism.

Declarations

Ethics approval and consent to participate

This prospective study was conducted in accordance with the Declaration of Helsinki (2008), Good Clinical Practice guidelines and local regulatory requirements (registration number, ID-RCB: NCT01383512; the study was registered on 28 June 2011 and updated on 11 October 2017). It was approved by the Brest University Hospital IRB (n°653). All subjects gave written consent to the inclusion of material pertaining to them.

Consent for publication

Not Applicable

Availability of data and materials

The corresponding author of this article will share all data that underlie the results reported in this article with qualified researchers who provide a valid research question.

Competing interests

The authors declare that they have no competing interests.

Funding

No funding was used for this study.

Authors' contributions

All authors contributed to all parts of this study and approved the final version of the manuscript.

All authors agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

All persons designated as authors qualify for authorship, and all those who qualify for authorship are listed.

Acknowledgements

We thank all those who participated from far or near in the achievement of this study.

References

1. Alt Murphy M, Resteghini C, Feys P, Lamers I. An overview of systematic reviews on upper extremity outcome measures after stroke. BMC Neurol. 2015;11:15-29. doi: 10.1186/s12883-015-0292-6.
2. Proud EL, Miller KJ, Bilney B, Balachandran S, McGinley JL, Morris ME. Evaluation of measures of upper limb functioning and disability in people with Parkinson disease: a systematic review. Arch Phys Med Rehabil. 2015;96(3):540-551.e1. doi: 10.1016/j.apmr.2014.09.016.
3. Lamers I, Kelchtermans S, Baert I, Feys P. Upper limb assessment in multiple sclerosis: a systematic review of outcome measures and their psychometric properties. Arch Phys Med Rehabil. 2014;95(6):1184-200.doi: 10.1016/j.apmr.2014.02.023.
4. Schwarz A, Kanzler CM, Lambercy O, Luft AR, Veerbeek JM. Systematic Review on Kinematic Assessments of Upper Limb Movements After Stroke. Stroke. 2019;50(3):718-727. doi: 10.1161/STROKEAHA.118.023531.

5. Bayle N, Fried SJ, Kappos EA, Hutin E, Fung K, Weisz DJ, Gracies JM. Movement Smoothness Differentiates Voluntary from Parkinsonian Bradykinesia. J Addict Res Ther. 2016;7:264. doi:10.4172/2155-6105.1000264.
6. Paparella G, Fasano A, Hallett M, Berardelli A, Bologna M. Emerging concepts on bradykinesia in non-parkinsonian conditions. Eur J Neurol. 2021;28(7):2403-2422. doi: 10.1111/ene.14851.
7. Marciniak C, McAllister P, Walker H, Brashear A, Edgley S, Deltombe T, Khatkova S, Banach M, Gul F, Vilain C, Picaut P, Grandoulier AS, Gracies JM; International AbobotulinumtoxinA Adult Upper Limb Spasticity Study Group. Efficacy and Safety of AbobotulinumtoxinA (Dysport) for the Treatment of Hemiparesis in Adults With Upper Limb Spasticity Previously Treated With Botulinum Toxin: Subanalysis From a Phase 3 Randomized Controlled Trial. PMR. 2017;9(12):1181-1190. doi: 10.1016/j.pmrj.2017.06.007.
8. Flash T, Hogan N, The coordination of arm movements: an experimentally confirmed mathematical model, J. Neurosci. 5 (1985) 1688–1703N. doi: 10.1523/JNEUROSCI.05-07-01688.1985.
9. Hogan N, D. Sternad D. Sensitivity of smoothness measures to movement duration, amplitude, and arrests. J. Mot. Behav. 41 (2009) 529–534. doi: 10.3200/35-09-004-RC.
10. Rohrer B, S. Fasoli S, Krebs H.I., Volpe B, Frontera W.R, Stein J, et al. Submovements grow larger, fewer, and more blended during stroke recovery. Motor Control 8 (2004) 472–483.doi: 10.1123/mcj.8.4.472.
11. Rohrer B, Fasoli S, Krebs HI, Hughes R, Volpe B, Frontera WR, et al. Movement smoothness changes during stroke recovery. J Neurosci. 15 sept 2002;22(18):8297-304.doi: 10.1523/JNEUROSCI.22-18-08297.2002.
12. Balasubramanian S, Melendez-Calderon A, Roby-Brami A, Burdet E. On the analysis of movement smoothness. J Neuroeng Rehabil. 2015 Dec 9;12:112. doi: 10.1186/s12984-015-0090.
13. Balasubramanian S, Melendez-Calderon A, Burdet E. A Robust and Sensitive Metric for Quantifying Movement Smoothness. IEEE Trans Biomed Eng. 2012;59(8):2126–136.doi: 10.1109/TBME.2011.2179545.
14. Cozens JA, Bhakta BB. Measuring movement irregularity in the upper motor neurone syndrome using normalised average rectified jerk. J Electromyogr Kinesiol. 2002 Feb;13(1):73-81. doi: 10.1016/s1050-6411(02)00070-6.
15. Celik O, O'Malley M.K, Boake C, Levin H.S, Yozbatiran N,and T. A. Reistetter T.A, "Normalized movement quality measures for therapeutic robots strongly correlate with clinical motor impairment measures," IEEE Trans. Neural Sys. Rehab. Eng., vol. 18, no. 4, pp. 433–444, 2010.doi: 10.1109/TNSRE.2010.2047600.
16. Mohamed Refai MI, Saes M, Scheltinga BL, van Kordelaar J, Bussmann JBJ, Veltink PH, Buurke JH, Meskers CGM, van Wegen EEH, Kwakkel G, van Beijnum BF. Smoothness metrics for reaching performance after stroke. Part 1: which one to choose? J Neuroeng Rehabil. 2021;18(1):154. doi: 10.1186/s12984-021-00949-6.

17. Engdahl SM, Gates DH. Reliability of upper limb movement quality metrics during everyday tasks. Gait Posture. 2019 Jun; 71:253-260. doi: 10.1016/j.gaitpost.2019.04.023.
18. David FJ, Robichaud JA, Vaillancourt DE, Poon C, Kohrt WM, Comella CL, Corcos DM. Progressive resistance exercise restores some properties of the triphasic EMG pattern and improves bradykinesia: the PRET-PD randomized clinical trial. J Neurophysiol. 2016 Nov 1;116(5):2298-2311. doi: 10.1152/jn.01067.2015.
19. Pila O, Duret C, Laborne FX, Gracies JM, Bayle N, Hutin E. Pattern of improvement in upper limb pointing task kinematics after a 3-month training program with robotic assistance in stroke. J Neuroeng Rehabil. 2017 Oct 13;14(1):105. doi: 10.1186/s12984-017-0315-
20. Saes M, Mohamed Refai MI, van Kordelaar J, Scheltinga BL, van Beijnum B-JF, Bussmann JBJ, et al. Smoothness metric during reach-to-grasp after stroke: part 2. longitudinal association with motor impairment. J Neuroeng Rehabil. 2021 Sep 24;18(1):144.doi: 10.1186/s12984-021-00937-w.
21. Frykberg GE, Grip H, Alt Murphy M. How many trials are needed in kinematic analysis of reach-to-grasp?-A study of the drinking task in persons with stroke and non-disabled controls. J Neuroengineering Rehabil. 2021 Jun 15;18(1):101. doi: 10.1186/s12984-021-00895-3.
22. Przybyla A, Good DC, Sainburg RL. Dynamic dominance varies with handedness: reduced interlimb asymmetries in left-handers. Exp Brain Res. 2012 Feb;216(3):419-31. doi: 10.1007/s00221-011-2946-y
23. Sawamura D, Sakuraba S, Yoshida K, Hasegawa N, Suzuki Y, Yoshida S, et al. Chopstick operation training with the left non-dominant hand. Transl Neurosci. 2021 Jan 1;12(1):385–95.
24. Wagner JM, Rhodes JA, Patten C. Reproducibility and minimal detectable change of three-dimensional kinematic analysis of reaching tasks in people with hemiparesis after stroke. Phys Ther. 2008 May;88(5):652–63.
25. Michaelsen SM, Levin MF. Short-term effects of practice with trunk restraint on reaching movements in patients with chronic stroke. Stroke. 2004;35:1914–9.
26. Alt Murphy M, Murphy S, Persson HC, Bergström U-B, Sunnerhagen KS. Kinematic analysis using 3D motion capture of drinking task in people with and without upper-extremity impairments. J Vis Exp. 2018;133:57228.

Tables

Table 1. Usual kinematic parameters (Mean±SD) for forward (FPM) and backward (BPM) movement of Set A (with pause in-between movements) and Set B (without pause in-between movements). Comparison of movements across types and sets. T-tests or Wilcoxon tests were used to compute p-values according to the normality of data assessed with a Shapiro-Wilk test. Cov = Coefficient of Variation; FBPM = Forward/backward pointing movement; D=dominant, ND= Non dominant.

		Movement Duration (s)		Index of Curvature		Peak Velocity (cm/s)		Peak Acc (cm/s^2)	
With pause (A)		**D**	**ND**	**D**	**ND**	**D**	**ND**	**D**	**ND**
FPM		1.40 (0.28)	1.31 (0.26)*	5.2 (2.1)	6.0 (2.9)**	84.8 (15.3)	86.0 (19.3)	462.0 (165.6)	486.6 (209.2)
	CoV inter	20.4	20.1	40.2	48.4	18.0	22.4	35.9	43.0
	CoV intra	11.4	13.7	21.5	25.9	6.6	7.1	12.8	14.4
BPM		1.06 (0.23)	1.10 (0.25)	5.5 (2.4)	6.5 (3.7) **	84.0 (20.1)	81.7 (18.6)	361.4 (151.2)	372.8 (157.2)
	CoV inter	21.6	22.3	44.0	56.6	23.9	22.8	41.8	42.2
	CoV intra	14.1	14.6	28.4	29.6	9.2	7.8	19.6	19.9
Without pause (B)									
FPM		0.92 (0.18)	0.92 (0.20)	4.4 (2.1)	5.1 (2.2)*	92.5 (18.0)	93.7 (22.0)	542.1 (201.6)	566.4 (245.6)
	CoV inter	20.1	21.7	47.3	41.9	19.5	23.5	37.2	43.4
	CoV intra	8.5	9.1	30.7	30.4	5.9	6.4	15.2	15.5
BPM		0.80 (0.18)	0.80 (0.21)	4.5 (2.7)	5.3 (3.0)**	88.9 (20.8)	88.5 (22.0)	386.6 (139.4)	405.7 (172.8)
	CoV inter	22.6	25.9	59.1	57.2	23.4	24.9	36.1	42.6
	CoV intra	9.3	8.5	27.5	25.3	8.5	8.6	15.8	17.5
		Forward vs Backward							
Differences	**Set A**	<0,000001	0.001	0.54	0.4	0.68	0.14	0.0006	0.0003
	Set B	0.00003	0.001	0.9	0.78	0.12	0.08	0.00001	0.000001
		With pause vs without pause							
	FPM	<0,000001	<0,000001	0.007	0.045	0.00008	0.00004	0.0006	0.0001
	BPM	<0,000001	<0,000001	0.04	0.02	0.07	0.005	0.24	0.08

Table 2. Smoothness parameters for forward (FPM) and backward (BPM) movement of Set A (with pause in-between movements) and Set B (without pause in-between movements).Comparison of movements smoothness across type and sets. T-tests or Wilcoxon tests are used to compute p-values according to the normality of data assessed with a Shapiro-Wilk test. Cov = Coefficient of Variation;

		N0C		NARJx10^3 (m/sec^3)		LDLJ		SPARC	
With pause (A)		**D**	**ND**	**D**	**ND**	**D**	**ND**	**D**	**ND**
FPM		6 (3)	5 (2)	46.4 (17.1)	42.1 (17.5)	-7.29 (0.50)	-7.14 (0.62)	-1.43 (0.02)	-1.45 (0.03)
	CoV inter	42.9	46.8	36.8	41.5	6.8	8.7	1.6	2.1
	CoV intra	36.4	39.7	26.0	30.1	5.1	6.4	1.6	1.9
BPM		3 (2)	4 (2)	26.1 (10.9)	29.2 (13.6)	-6.48 (0.64)	-6.64 (0.52)	-1.48 (0.06)	-1.48 (0.06)
	CoV inter	49.5	46.4	41.7	46.7	9.8	7.8	4.2	3.8
	CoV intra	50.2	52.8	33.2	32.1	8.2	6.6	3.2	3.2
Without pause (B)									
FPM		2 (1)	3(1)	20.2 (7.9)	20.5 (6.9)	-6.32 (0.53)	-6.41 (0.44)	-1.45 (0.03)	-1.44 (0.03)
	CoV inter	34.6	32.2	39.3	33.8	8.4	6.9	2.2	1.9
	CoV intra	26.8	29.3	18.1	21.1	5.0	5.9	1.9	1.8
BPM		1 (1)	2 (1)*	13.9 (6.6)	13.9 (6.1)	-5.56 (0.52)	-5.58 (0.53)	-1.48 (0.05)	-1.48 (0.05)
	CoV inter	41	46.8	47.0	43.8	9.4	9.4	3.3	3.3
	CoV intra	24.9	36.3	20.7	21.3	5.8	5.6	3.1	3.5
		Forward vs Backward							
Differences	**Set A**	0.0001	0.033	0.00001	0.004	0.000003	0.001	0.002	0.009
	Set B	0.000004	0.00001	0.000004	<0.00001	<0,000001	<0,000001	0.011	0.001
		With pause vs without pause							
	FPM	0.000002	0.000006	0.000001	0.000001	<0,000001	<0,000001	0.075	0.259
	BPM	0.000003	0.000002	0.000002	0.000001	<0,000001	<0,000001	0.422	0.779

Figures

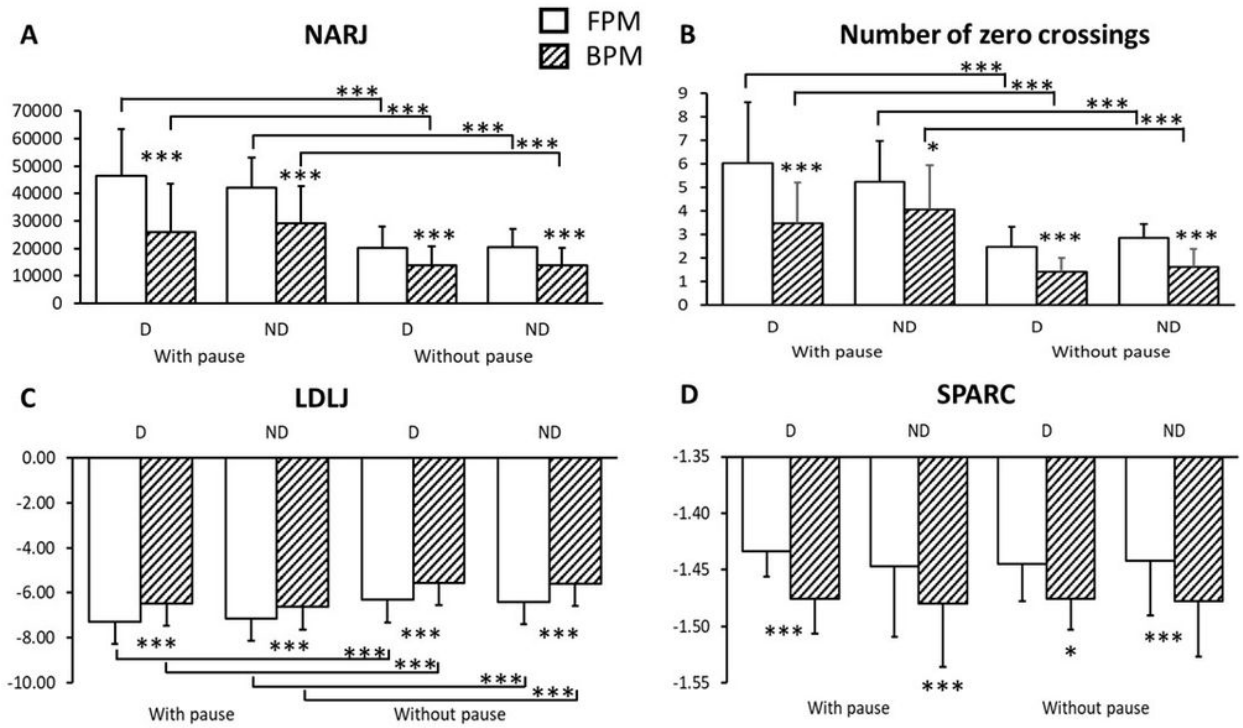

Figure 1

Differences in smoothness across sides and movement type (forward vs backward) for all smoothness measures.

FBPM = Forward/backward pointing movement; D=dominant, ND= Non dominant.

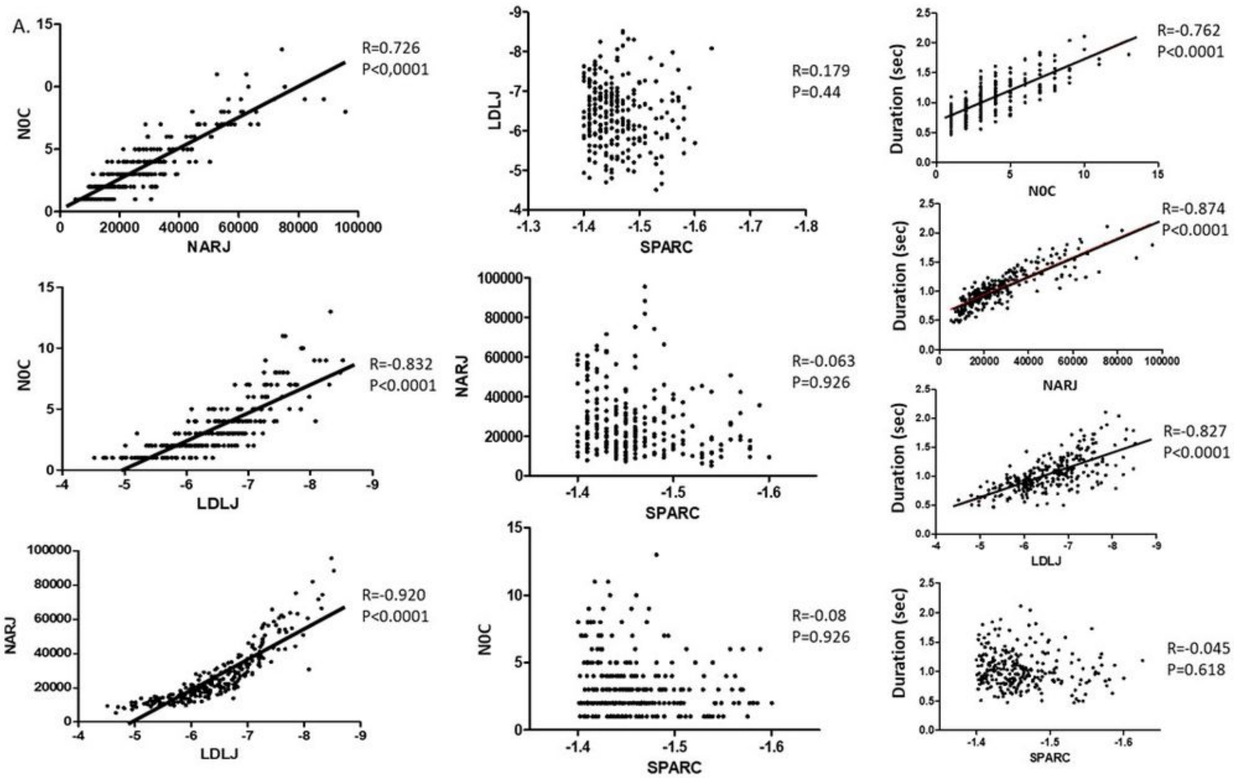

Figure 2

A. Correlations between smoothness measures from temporal domain. B. Correlations between SPARC and other smoothness measures. C. Correlations between smoothness measures and movement duration.

Figure 3

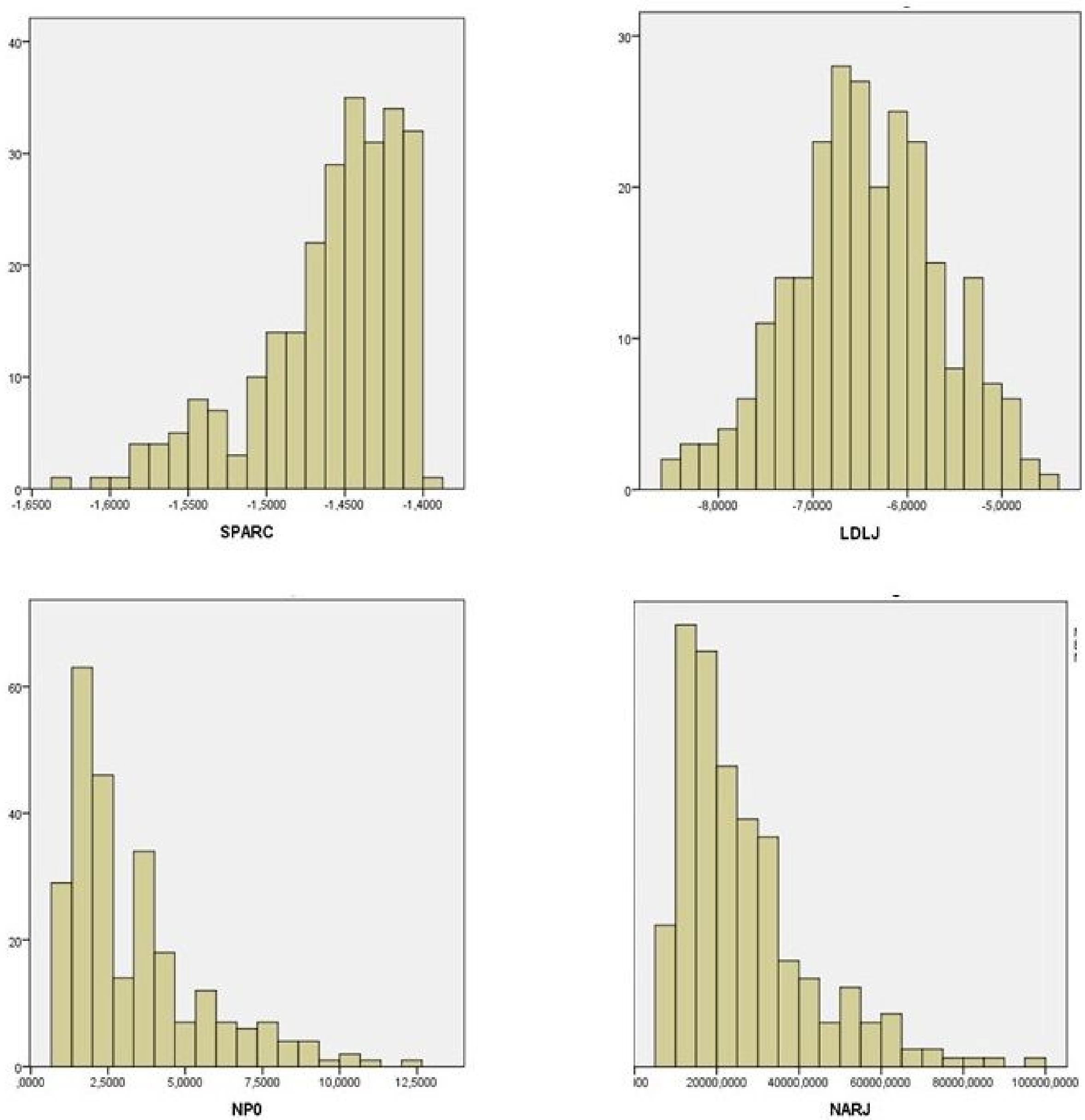

Figure 3

Legend not included with this version.