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Analysis of reaching movements of upper arm in robot assisted exercises

Kinematic assessment of robot assisted upper arm reaching single-joint movements

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ABSTRACT. Robot-mediated therapy (RMT) has been a very dynamic area of research in recent years. Robotics devices are in fact capable to quantify the performances of a rehabilitation task in treatments of several disorders of the arm and the shoulder of various central and peripheral etiology. Different systems for robot-aided neuro-rehabilitation are available for upper limb rehabilitation but the biomechanical parameters proposed until today, to evaluate the quality of the movement, are related to the specific robot used and to the type of exercise performed. Besides, none study indicated a standardized quantitative evaluation of robot assisted upper arm reaching movements, so the RMT is still far to be considered a standardised tool. In this paper a quantitative kinematic assessment of robot assisted upper arm reaching movements, considering also the effect of gravity on the quality of the movements, is proposed. We studied a group of 10 healthy subjects and results indicate that our advised protocol can be useful for characterising normal pattern in reaching movements.

Key words: *robot-mediated-therapy, rehabilitation, reaching-movements, kinematic, gravity, minimum jerk, smoothness, upper limb, bell-shaped, activity daily living.*

RIASSUNTO. Negli ultimi anni la riabilitazione robotica (RMT) ha rappresentato un'area di ricerca molto dinamica. I dispositivi robotici sono, infatti, in grado di quantificare le prestazioni dei task riabilitativi nel trattamento di numerose patologie dell'arto superiore di eziologia ortopedica o neurologica. Esistono numerosi sistemi robotici per la riabilitazione dell'arto superiore ma i parametri biomeccanici utilizzati sono ancora spesso legati alla tipologia di robot utilizzato. Inoltre, nessuno studio ha proposto una valutazione quantitativa standardizzata dei movimenti di reaching dell'arto superiore, e ciò suggerisce che la RMT è ancora lontana dall'essere considerata uno strumento standardizzato di valutazione. In tale lavoro viene proposta una valutazione cinematica quantitativa dei movimenti di reaching robot-assistiti, andando ad investigare anche gli effetti della forza di gravità sulla qualità cinematica di tali movimenti. Per tale studio sono stati arruolati 10 soggetti sani ed i risultati ottenuti indicano che il nostro protocollo di valutazione può essere un valido aiuto per la caratterizzazione dei movimenti di reaching nei soggetti sani.

Parole chiave: riabilitazione robotica, movimenti di reaching, cinematica, gravità, minimum jerk, smoothness, arto superiore, profilo a campana, activitydaily living.

Introduction

Reaching movement (RM) is a movement executed towards a given target and represents a basic movement of the upper extremities, veryimportant for independence in daily living activities such as self-feeding, grooming, dressing and environmental switch operations (1-2). RM from one target to another can be single-joint or multi-joint (3-4).

The former involves a curvilinear movement of the hand, whereas the latter can also be straight. In any case, many studies in this field proved that some common features, defined *invariant kinematics*or *regularities* (5), can be identified.First, hand paths in rest-to-rest movements tend to be roughly straight (or, slightly curved) and smooth. Second, the velocity profile of the hand trajectory is bell shaped(6-8). Actually, the velocity profile can show single or multiple peaks, however, each peak is always bell-shaped and the shape of the hand trajectory can be always decomposed in a succession of straight tracts (9, 10).

In the last few years, the RM derive their growing importance not only by the contribution they give to the understanding of the movement physiology, but also to their diffusion in rehabilitative field. Upper limb RM are in fact the most used motor task in rehabilitation treatments of several disorders of the arm and the shoulder of various central and peripheral etiology (11-13).

Physical therapy is used as a means for helping patients with impairments to regain lost motor function but the existing clinical measures of motor impairment are coarsely quantified and subjective.In order to tailor the therapy programs to individual characteristics of subjects, highly sensitive measures of motor impairment are necessary to recognise even small differences in patient's response to different courses of therapy. An objective, finely quantified and standardized measure may allow a better understanding how different factors affect response to therapy.So,rehabilitators have focused increasing attention on the quantitative evaluation of residual motor abilities.

Some research groups have studied and developed mechatronic and robotic systems for rehabilitation which allow the patient to perform repetitive and goal-oriented movements which permit a safe and intensive training that can be done in combination with other types of treatment. The robot accompanies, and possibly completes, the movement performed by the patient according to his residual motor skills. In robot-mediated therapy (RMT), the therapeutic practice is accomplished by asking the subject to perform several exercises such as to reach different fixed virtual targets that aredisplayed to the patient on a horizontal row, or to draw a circular trajectory in a virtual plane with and without the robot impedance-based assistance providing a constraint along the requested trajectory (14, 15). A useful advantage of this treatmentis the possibility to evaluate kinematic and dynamic parameters during the movement of the limb, while clinical scales permit only qualitative and potentially disagreeing evaluations, often carried out by different therapists (15, 16-18). Kinematicparameters can be used to measure the progress of the patient in a more objective way and to adapt the rehabilitation exercise according to the specific needs of the patient. In this way, treatment efficacy and the motor outcome may be optimized. Patient autonomy may increase as a result, permitting an early reinstatement in the social and work environment and a consequent reduction in health care costs (19).

Nevertheless, although RMT has been a very active area of research in recent years and it holds much promise for improved motor outcomes (13), there is still lacking of a standardization of quantitative kinematic indexes and rehabilitation protocols proposed. The lack of a standard for robotic treatments is caused partly by the non-standardized nature of current robot-assisted therapy. Each of the existing robotic devices is unique in its number of degrees of freedom, the types of movement it supports, the number and types of sensors used, and the basic control strategy used to control the robot's interaction with a subject. Thus, it is not known how assessment made on one particular robotic device compare with similar assessment made with another device (20).

Besides, despite to the benefits motors achieved thanks to RMT, another limit of this technique isthe lack of information that show improvements on "activity of daily living"(measures ADL) (21, 22). For example, how can the smoothness of reaching movements be used for tailoring therapeutic intervention that aims to improve a subject's use of his/her arm in activity of daily living? (20). This may be due to the fact that most of the existing robotic devices are programmed to produce simple stereotyped movements of the limbs, often not related to the functional activities included in measures ADL (23-25).

Finally, another problem of the literature about RMT is that very few studies (26) have examined the effect of the gravity on the quality of RM. In fact, the majority of rehabilitation studies have investigated these movements by working in the horizontal plane in such a way to kept constant the influence of gravity (15, 19).

So the aim of this paper is to propose a quantitative kinematic assessment of robot assisted upper arm reaching single-joint movements of the shoulder,by means of evaluation metrics supplied by the robot device, taking advantage of the speed profile shape that is the kinematic invariant of all point-to-point RM, using relatively simple indexes typical of a Gaussian profile which corresponds to a regular movement. In particular, we wanted to describe the normal patterns obtained by healthy subjects,considering also the effect of gravity on the quality of these movements.

Material and Methods

Measurement protocol

For this study, 10 healthy adult subjects (35±8 year old, males) have been enrolled. Each subject has been underwent to 2 sessions, with at least intervals of 15' of resting time between them. Each session consists of6 trial composed by4 reaching tasks (2horizontal and 2vertical),with at least intervals of 1' of resting time between two trials. Each trialhas been executed at two different target amplitudes, of 20° and 30°, and at three different target velocities, respectively of 20°/s, 30°/s and 40°/s. The task required each subject to move the hand from the center position to the target and then return to the center with a sequence of 2single-joint movements (Table I and II), without requiring the fully extension of the arm. For each trial, the sequence of tasks has been randomly set. The shoulder rehabilitation device used has been the Multi-Joint-System (in the following MJS) of the Tecnobody, a mechanical arm provided with four "freedom" ranges, giving the patient freedom of jointmovement in the three fundamental axes of movement: Anterior-Posterior, Adduction-Abduction, Internal rotation-External rotation (Figure 1).

During the session, subjects have been asked to seat onthe ergonomic chair of the robot with the trunk erected, neck straight fixing the central green starting point on the front monitor (green circle with letter "H" in Figure 2). The arm under test holding the robot grip by the hand in

Table I. ***Description of the movements sequence in horizontal reaching tasks***

Task	Acronym	Meaning	Description
External	EH1	External Horizontal 1	Horizontal abduction of the right (left) shoulder from the middle position to the outer right (left)
	IH1	Internal Horizontal 1	Horizontal adduction of the right (left) shoulder from the right external position (left) to the middle one
Internal	IH2	Internal Horizontal 2	Horizontal abduction of the right (left) shoulder from the middle position to left (right) external one
	EH2	External Horizontal 2	Horizontal adduction of the right (left) shoulder from the outer left (right) position to the middle one

Table II. ***Description of the movements sequence in vertical reaching tasks***

Task	Acronym	Meaning	Description
Up	UV1	Up Vertical 1	Elevation of the shoulder from the middle position to the top
	DV1	Down Vertical 1	Lower down of the shoulder towards the middle position
Down	DV2	Down Vertical 2	Lower down of the shoulder from the middle position to the bottom
	UV2	Up Vertical 2	Elevation of the shoulder from the bottom towards the middle position

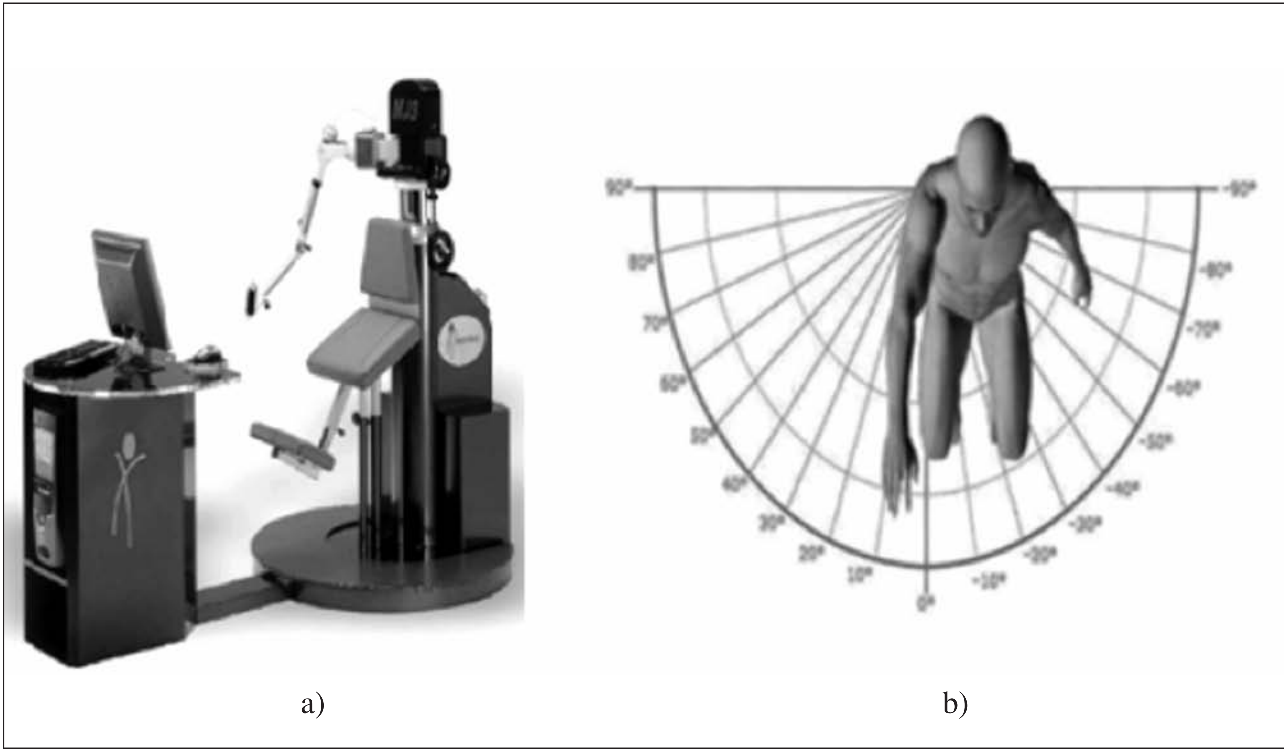

Figure 1. ***a) a picture of the MJS produced by Tecnobody and used in the lab. The picture shows a subject sit on the ergonomic chair of the robot in making his exercise; b) top view of the anatomic position***

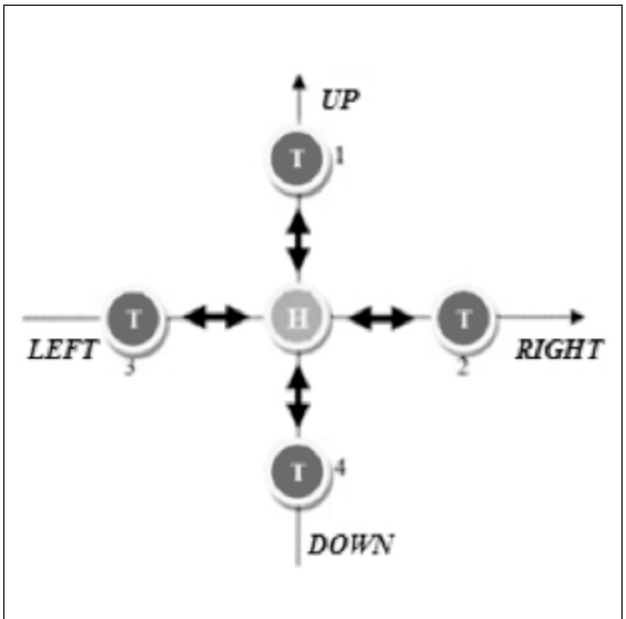

Figure 2. ***The visually-guided planar reaching task***

a position parallel to the floor at 90° with the trunk (anatomic position), the arm not under test on side handle close to the seat.

During all movements analysed in this article, the MJS was unpowered and acted as passive measurement devices. Kinematic task consists on a visually-guided nearly planarreaching task. Four targets are equally spaced of 20° or 30° (really the arm reaches each new position covering a 20° or 30° angle) around a center target (Fig. 2) and visual feedback of both target and robot handle location are provided on a computer screen in front of the robot.

The protocol has been implemented in the Movement Analysis Laboratory of the Research Institute "Salvatore Maugeri Foundation", Benevento (Italy) and approved by the internal scientific technical committee. All participants gave their informed consent.

Signal processing

Spatial coordinates of the handle position, related to the range of motion of the shoulder, have been recorded with a 1/10° degree resolution and sampled at a sampling rate of 20 Hz. Velocity profiles have been computed using a derivative algorithm. Since differentiation degrades signal-to-noise ratio, the filter has to be carefully chosen. To this aim has been used aSavitzky-Golay filter of third order and of frame length 41.

Movement's onset/end times were calculated on the velocity profile in correspondence of successive zero values. In order to avoid to consider false positives, only zero values with an interval distance equal to the set angular excursion of the specific task were accepted.

Kinematic analysis

Quantitative kinematic analysis of the RM has been describedboth by morphological indexes, symmetry coefficient and smoothness, and by statistical indexes, kurtosis and skewness. While smoothness is a typical kinematic measure in RM (1, 26), the other ones are indexes previously introduced by the authors (27-32). Symmetry coefficient, an index introduced to investigate the shape of the velocity profile,is calculated as the ratio between the time interval from the peak of the velocity to the end of the movement (deceleration time) and from the onset to the peak of the velocity (acceleration time).

The tendency of human movements to be characteristically smooth and graceful, led to suggest (10, 18, 26, 33) that the motor coordination can be mathematically modelled by postulating the voluntary movement are executed, at least in the absence of any other overriding concerns, in a way to be as smooth as possible. In according with this theory, smoothness estimation is based on the minimum jerk theory stating that any single-joint movement will have maximum smoothness when the magnitude of the J parameter (rate of the change of acceleration with respect to time - third time derivative of the position) is minimized over the duration of the movement. Particularly, it has been demonstrated that in order to produce a maximum smoothness movement, one must minimize the jerk cost functional defined as

$$J = \int_0^d \left| \frac{d^3x(t)}{dt^3} \right|^2 dt$$

The integrated squared jerk has dimensions of amplitude squared divided by the 5th power time (A^2/D^5). In order to have a measure of the movement's smoothness without any dependency on its duration and amplitude, amongthe different ways to normalize jerk-based measures proposed in literature (34), we have chosenthe following dimensionless jerk measure (Eq. 1):

$$J = \frac{D^5}{A^2} \int_{t_0}^{t_f} | \frac{d^3\mathrm{x(t)}}{dt^3} |^2 \quad (1)$$

where x(t) is the angular displacement, t_0 and t_f are start and end time of the movement, $D=t_f-t_0$ its duration and A its amplitude.

As has been frequently observed (9, 10) and mentioned in the section introduction, single-joint movements are characterized by single-peaked, bell-shaped gaussian-likespeed profiles. Hence, a different way to describe each movement is to consider statistical indexes typical of a Gaussian distribution. On this basis, the signal can be described statistically like a probability density function respectively by means of k-order moments or k-order central moments, Eq. (3).

$$3)\ M_K = E[(x - M_1)^k]$$

Of particular interest appear the third and fourth order central moment, respectively named skewness and kurtosis. The skewness coefficient describes the symmetry of the shape, with a zero value in case of symmetry, a positive or a negative value respectively in case of a right or left asymmetry. The kurtosis coefficient describes the flatness of the shape, with a three value (normokurtosis)in case of a gaussian bell-shape flatness. Distributions with negative or positive excess kurtosis are called platykurtic distributions or leptokurtic distributions respectively.

Kinematics indexes are reported as mean ± standard deviation at the two amplitude's values and at the three different target velocities.

Statistical analysis

In order to test if differences obtained in indexes' values are due to chance or to the type of movement we have carried out a statistical analysis.

Distributions of kinematic indexes have been tested for normality by D'Agostino-Pearson omnibus K2 normality test, and since to the non-normality of the data differences within each type of movement(Horizontal, Up-Vertical and Down-Vertical) due to amplitude and/or velocity have been compared using the Kruskal-Wallis test. Multiple comparisons of each kinematic variable (Kurtosis, Skewness, Smoothness, Symmetry) have been then performed by means of the post-hoc Dunnett's test.

Besides, in order to test differences due to the different type of movement (horizontal or vertical at fixed amplitude and velocity) a Mann Whitney testhas been used.

Results

Subjects have underwent the above described motor taskson their dominant shoulder for a total of 960 RM. Data were offline analysed and merged in horizontal external and internalRM (EH1, EH2, IH1, IH2), up vertical anti-gravity RM (UV1, UV2) and down vertical RM(DV1, DV2).

As example, the position signalsof all movements corresponding to a horizontal task at amplitude of 30° and at velocity of 20°/s and of a vertical task at amplitude of 30° and velocity of 40°/s are reported in Fig. 3 and in Fig. 4 respectively.

Results of the kinematic analysisare reported in Table III-V. In Table VI we reported a summary of results of the

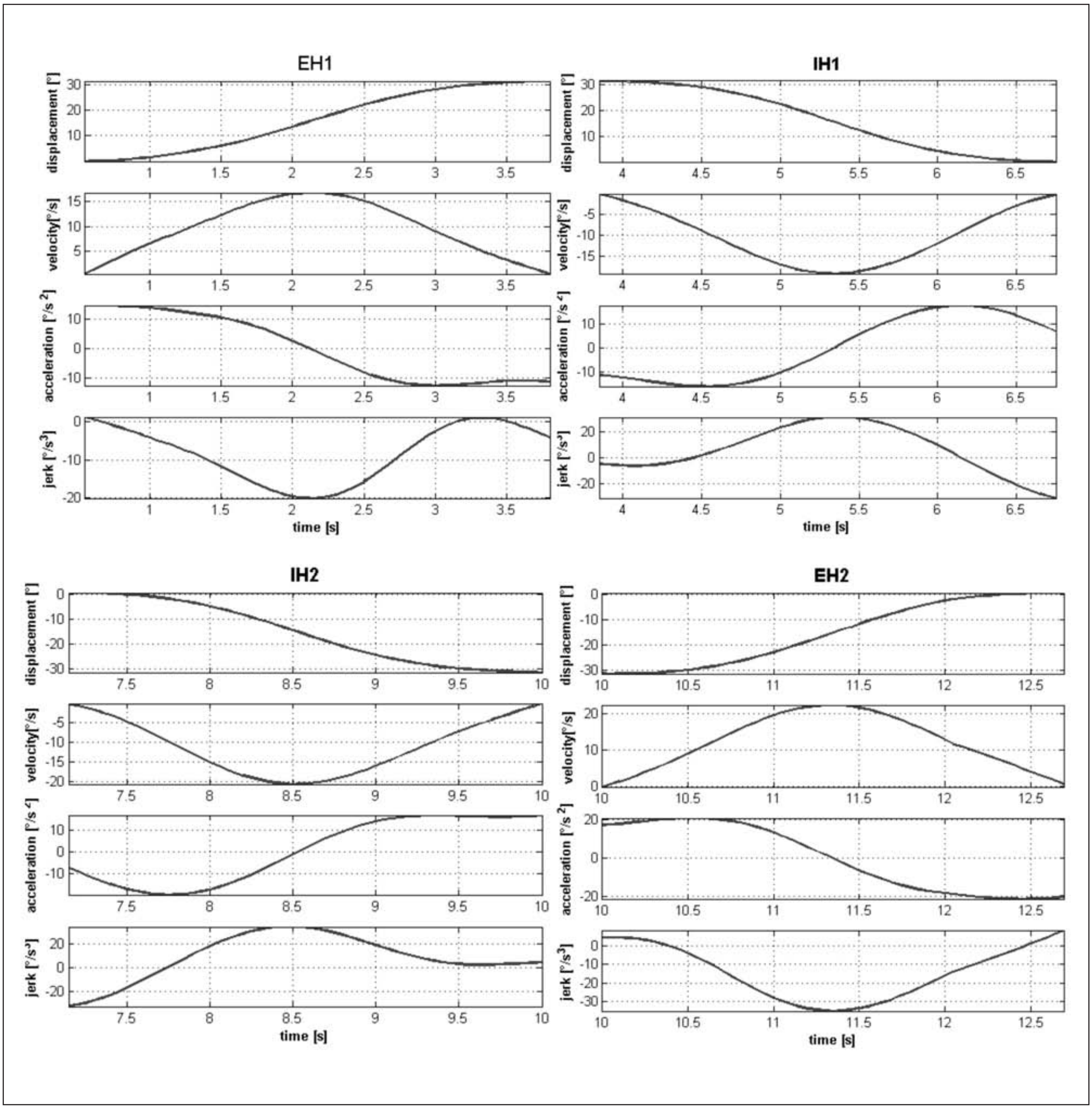

Figure 3. ***horizontal task at amplitude of 30° and velocity of 20°/s***

Kruskal-Wallis test (*** for statistically highly significant: $p < 0.001$; ns for not significant). In Appendix A we report other results of statistical analysis.

By the analysis of the results reported in Tables III-V can be observed that all the indexes decrease their value with increasing velocity and increase with a greater movement's amplitude. More important, on the basis of these results, better values, i.e. closer to those theoretical, can be obtained for movements at highest velocities and lowest amplitude values, if symmetry, smoothness or skewness are considered (let us remember that theoretical values are 1, minimum and 0 respectively).

Nevertheless, for kurtosis index, values closest to the theoretical value of 3 have been obtained at lowest velocities and greatest amplitudes in all cases. Besides, by Table VI (and in more detail in Appendix A), it is possible to observe that, fixing the type of movement and assessing the dependence on amplitude and velocity, in horizontal movements the Kruskal-Wallis test is resulted significant only for smoothness index. In vertical movements, the Kruskal-Wallis test is resulted significant for all indexes, however the smoothness is resulted more sensible to changes in these parameters (amplitude and velocity) with respect to the other ones, in fact the Dunn's multiple comparison test has highlighted significant results between pairs of RM (at different values of velocity and amplitude) in a greater number of cases (please refer to Appendix A and Table VII - X).

Further, the changes in the values of smoothness index are almost always statistically significant also fixing amplitude and velocity and by comparing type of movement (Table XI).

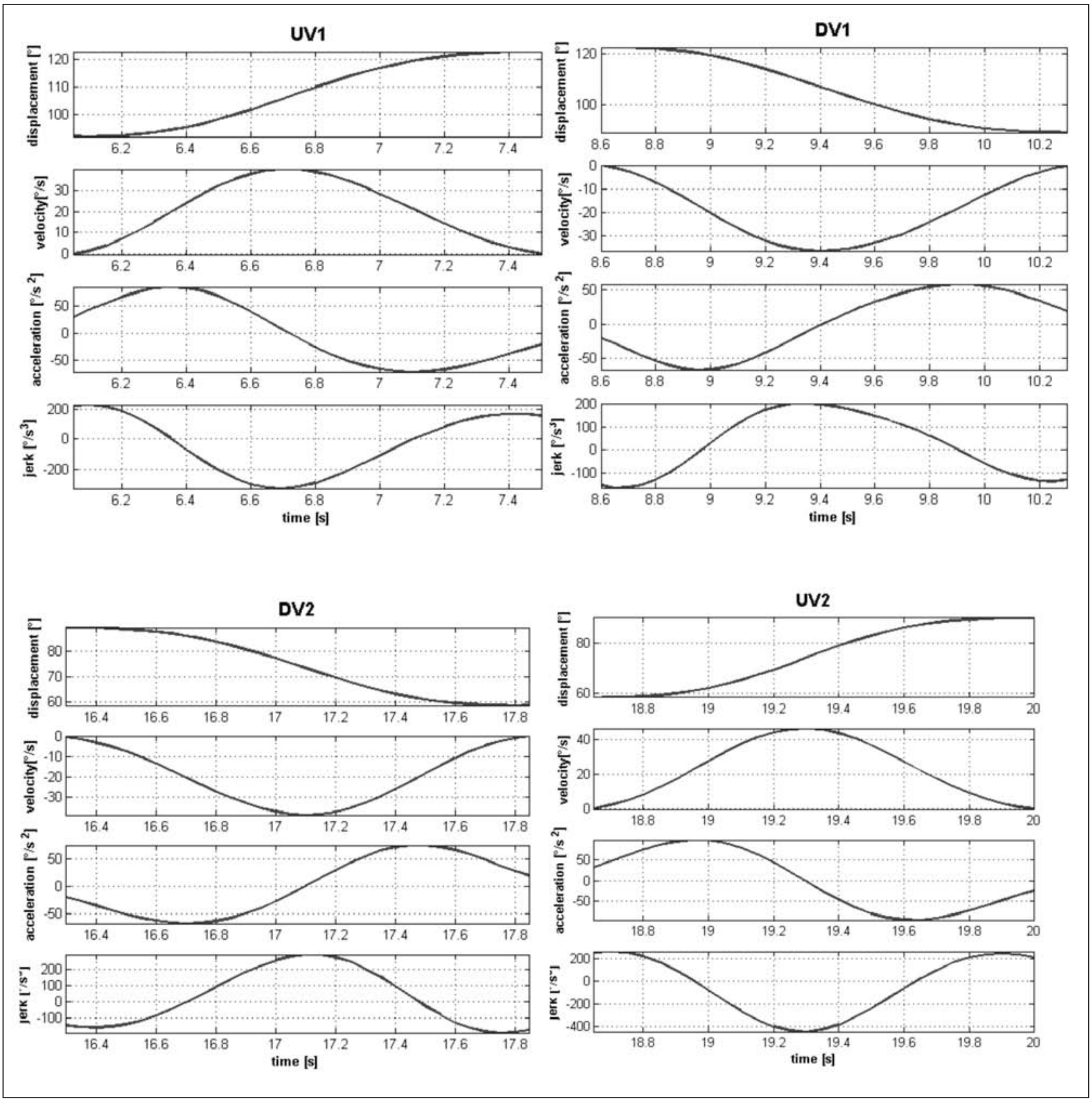

Figure 4. *Vertical task at amplitude of 30° and velocity of 40°/s*

Table III. *Kinematic Indexes (mean ± standard deviation) at the two amplitude's values and at the three different target velocities for the horizontal reaching movements*

	Amplitude [°]	Vel. 20°/s	Vel. 30°/s	Vel. 40°/s
Symmetry	**20°**	1.11±0.43	1.10±0.29	1.09±0.17
	30°	1.27±0.60	1.19±0.48	1.10±0.22
Smoothess	**20°**	258±168	158±66	115±19
	30°	309±162	203±121	132±40
Skewness	**20°**	0.02±0.34	0.03±0.20	0.01±0.08
	30°	0.05±0.36	0.08±0.37	0.05±0.12
Kurtosis	**20°**	2.61±0.66	2.47±0.27	2.39±0.04
	30°	2.70±0.77	2.58±0.52	2.40±0.10

Table IV. *Kinematic Indexes (mean ± standard deviation) at the two amplitude's values and at the three different target velocities for the up vertical reaching movements*

	Amplitude [°]	Vel. 20°/s	Vel. 30°/s	Vel. 40°/s
Symmetry	20°	1.24±0.27	1.04±0.29	1.00±0.25
	30°	1.35±0.59	1.24±31	1.14±0.29
Smoothess	20°	503±309	255±120	133±60
	30°	539±175	340±136	200±117
Skewness	20°	0.15±0.15	0.01±0.15	0.00±0.14
	30°	0.24±0.27	0.16±0.16	0.05±0.14
Kurtosis	20°	2.44±0.2	2.40±0.08	2.30±0.08
	30°	2.46±0.42	2.46±0.12	2.36±0.09

Table V. *Kinematic Indexes (mean ± standard deviation) at the two amplitude's values and at the three different target velocities for the down vertical reaching movements*

	Amplitude [°]	Vel. 20°/s	Vel. 30°/s	Vel. 40°/s
Symmetry	20°	1.32±0.35	1.10±0.30	1.00±0.33
	30°	1.40±0.54	1.11±0.29	1.04±0.35
Smoothess	20°	500±155	314±116	200±55
	30°	512±174	358±136	273±96
Skewness	20°	0.20±0.26	0.02±0.15	0.00±0.17
	30°	0.23±0.43	0.04±0.17	0.01±0.18
Kurtosis	20°	2.57±0.44	2.44±0.05	2.38±0.04
	30°	2.69±0.76	2.49±0.16	2.43±0.06

Table VI. *p value summary of the Kruskal-Wallis test used to test differences in indexes values due to different amplitude and velocity (but with the same type of movement)*

	Horizontal RM	Up vertical RM	Down vertical RM
Symmetry	ns	***	***
Smoothness	***	***	***
Skewness	ns	***	***
Kurtosis	ns	***	***

ns = not significant; *** = highly significant

Discussion

In this work, we have chosen to study single joint RM because some studies have demonstrated that these movements represent powerful models for understanding the neural mechanisms that underlie control of movement speed and distance (35, 36). In particular, we have chosen to study single-joint movements of the shoulder because it is an important part of upper limb motion (37), which plays a critical role in stabilizing and orients the upper limb during everyday movements and its mobility is commonly recruited for compensatory movements.

The aim of this work has been to propose a more standardized evaluation of differentshoulder RM performed during RMT, taking advantage of the invariant kinematics of the bell shaped speed profile during point-to-point single-joint movements.

So, we have chosen typical indexes used to characterize the Gaussian distribution and a symmetry index evaluated

Table VII. ***In the upper part of the table are shown the differences in Simmetry index value due to different amplitude and velocity evaluated by the Kruskal-Wallis test; then the post-hoc multiple comparison analysis in order to test difference between difference groups was performed***

	Horizontal RM	Signif.	Up Vertical RM	Signif.	Down vertical RM	Signif.
Kruskal-Wallis test						
P value	0.0993	ns	P<0.0001	***	P<0.0001	***
Kruskal-Wallis statistic	9.254		62.74		50.59	
Dunn's Multiple Comp.test	Diff. in rank sum		Diff. in rank sum		Diff. in rank sum	
20-20 vs 20-30	-21.07	ns	114.8	***	77.85	***
20-20 vs 20-40	-28.81	ns	126.8	**	126.0	*
20-20 vs 30-20	-81.77	ns	-2.540	ns	-9.052	ns
20-20 vs 30-30	-60.34	ns	-17.87	ns	74.38	**
20-20 vs 30-40	-35.17	ns	53.59	ns	112.4	***
20-30 vs 20-40	-7.738	ns	11.98	ns	48.19	ns
20-30 vs 30-20	-60.70	ns	-117.4	**	-86.90	*
20-30 vs 30-30	-39.26	ns	-132.7	***	-3.465	ns
20-30 vs 30-40	-14.09	ns	-61.25	*	34.52	ns
20-40 vs 30-20	-52.96	ns	-129.4	*	-135.1	*
20-40 vs 30-30	-31.53	ns	-144.7	**	-51.66	ns
20-40 vs 30-40	-6.356	ns	-73.23	ns	-13.67	ns
30-20 vs 30-30	21.43	ns	-15.33	ns	83.43	*
30-20 vs 30-40	46.60	ns	56.13	ns	121.4	***
30-30 vs 30-40	25.17	ns	71.46	*	37.99	ns

RM = reaching movement; ns = not significant; * = significant; ** = very significant; *** = highly significant; in the pairs of numbers shown as x-y, the first number (x) is the amplitude of the movement and the second one (y) its velocity.

Table VIII. ***In the upper part of the table are shown the differences in Kurtosys index value due to different amplitude and velocity evaluated by the Kruskal-Wallis test; then the post-hoc multiple comparison analysis in order to test difference between difference groups was performed***

	Horizontal RM	Signif.	Up Vertical RM	Signif.	Down vertical RM	Signif.
Kruskal-Wallis test						
P value	0.0507	ns	P<0.0001	***	P<0.0001	***
Kruskal-Wallis statistic	11.04		73.19		58.74	
Dunn's Multiple Comp.test	Diff. in rank sum		Diff. in rank sum		Diff. in rank sum	
20-20 vs 20-30	2.624	ns	68.28	**	102.3	***
20-20 vs 20-40	90.36	ns	205.5	***	213.0	***
20-20 vs 30-20	44.91	ns	57.07	ns	76.73	*
20-20 vs 30-30	0.5597	ns	-24.70	ns	40.09	ns
20-20 vs 30-40	91.68	ns	118.3	***	114.3	***
20-30 vs 20-40	87.74	ns	137.2	**	110.7	ns
20-30 vs 30-20	42.29	ns	-11.21	ns	-25.52	ns
20-30 vs 30-30	-2.064	ns	-92.98	***	-62.16	ns
20-30 vs 30-40	89.06	ns	50.04	ns	12.03	ns
20-40 vs 30-20	-45.45	ns	-148.4	*	-136.2	*
20-40 vs 30-30	-89.80	ns	-230.2	***	-172.9	**
20-40 vs 30-40	1.322	ns	-87.16	ns	-98.68	ns
30-20 vs 30-30	-44.35	ns	-81.77	ns	-36.64	ns
30-20 vs 30-40	46.77	ns	61.25	ns	37.55	ns
30-30 vs 30-40	91.12	ns	143.0	***	74.20	*

RM = reaching movement; ns = not significant; * = significant; ** = very significant; *** = highly significant; in the pairs of numbers shown as x-y, the first number (x) is the amplitude of the movement and the second one (y) its velocity.

Table IX. *In the upper part of the table are shown the differences in Skewness index value due to different amplitude and velocity evaluated by the Kruskal-Wallis test; then the post-hoc multiple comparison analysis in order to test difference between difference groups was performed*

	Horizontal RM	Signif.	Up Vertical RM	Signif.	Down vertical RM	Signif.
Kruskal-Wallis test						
P value	0.0536	ns	P<0.0001	***	P<0.0001	***
Kruskal-Wallis statistic	26.16		124.7		84.01	
Dunn's Multiple Comp.test	Diff. in rank sum		Diff. in rank sum		Diff. in rank sum	
20-20 vs 20-30	-3.647	ns	143.4	***	122.4	***
20-20 vs 20-40	-32.63	ns	168.6	***	219.5	***
20-20 vs 30-20	-143.0	ns	-100.7	**	-8.144	ns
20-20 vs 30-30	-61.97	ns	-13.30	ns	103.2	***
20-20 vs 30-40	-44.09	ns	89.47	***	120.1	***
20-30 vs 20-40	-28.98	ns	25.24	ns	97.10	ns
20-30 vs 30-20	-139.3	ns	-244.1	***	-130.5	***
20-30 vs 30-30	-58.32	ns	-156.7	***	-19.11	ns
20-30 vs 30-40	-40.44	ns	-53.89	ns	-2.242	ns
20-40 vs 30-20	-110.4	ns	-269.3	***	-227.6	***
20-40 vs 30-30	-29.34	ns	-181.9	***	-116.2	ns
20-40 vs 30-40	-11.46	ns	-79.13	ns	-99.35	ns
30-20 vs 30-30	81.02	ns	87.43	ns	111.4	**
30-20 vs 30-40	98.90	ns	190.2	***	128.3	***
30-30 vs 30-40	17.88	ns	102.8	***	16.87	ns

RM = reaching movement; ns = not significant; * = significant; ** = very significant; *** = highly significant; in the pairs of numbers shown as x-y, the first number (x) is the amplitude of the movement and the second one (y) its velocity.

Table X. *In the upper part of the table are shown the differences in Smoothness index value due to different amplitude and velocity evaluated by the Kruskal-Wallis test; then the post-hoc multiple comparison analysis in order to test difference between difference groups was performed*

	Horizontal RM	Signif.	Up Vertical RM	Signif.	Down vertical RM	Signif.
Kruskal-Wallis test						
P value	P<0.0001	***	P<0.0001	***	P<0.0001	***
Kruskal-Wallis statistic	252.6		245.1		181.3	
Dunn's Multiple Comp.test	Diff. in rank sum		Diff. in rank sum		Diff. in rank sum	
20-20 vs 20-30	224.2	***	185.2	***	154.4	***
20-20 vs 20-40	415.8	***	315.3	***	295.8	***
20-20 vs 30-20	-64.50	ns	-41.80	ns	-5.081	ns
20-20 vs 30-30	137.1	***	96.10	***	110.8	***
20-20 vs 30-40	329.1	***	238.7	***	195.4	***
20-30 vs 20-40	191.5	**	130.0	**	141.4	**
20-30 vs 30-20	-288.7	***	-227.0	***	-159.5	***
20-30 vs 30-30	-87.16	*	-89.13	***	-43.61	ns
20-30 vs 30-40	104.9	**	53.45	ns	41.03	ns
20-40 vs 30-20	-480.3	***	-357.1	***	-300.9	***
20-40 vs 30-30	-278.7	***	-219.1	***	-185.0	***
20-40 vs 30-40	-86.67	ns	-76.57	ns	-100.3	ns
30-20 vs 30-30	201.6	***	137.9	***	115.9	**
30-20 vs 30-40	393.6	***	280.5	***	200.5	***
30-30 vs 30-40	192.0	***	142.6	***	84.64	**

RM = reaching movement; ns = not significant; * = significant; ** = very significant; *** = highly significant; in the pairs of numbers shown as x-y, the first number (x) is the amplitude of the movement and the second one (y) its velocity.

Table XI. ***Changes in the values of smoothness index at fixed amplitude and velocity comparing different type of movement (Mann-Whitney test)***

		20-20	20-30	20-40	30-20	30-30	30-40
H RM vs V RM	P value	P<0.0001	P<0.0001	0.93	P<0.0001	P<0.0001	0.0003
	P value summary	***	***	ns	***	***	***
	Sum of ranks	50774.49	31717.32	816.56	3467.24	15078.17	12495.15
	Mann-Whitney U	7409	6066	320	386	2988	4869
H RM vs D RM	P value	P<0.0001	P<0.0001	P<0.0001	P<0.0001	P<0.0001	P<0.0001
	P value summary	***	***	***	***	***	***
	Sum of ranks	48834.43	27331.37	511.67	3484.21	13852.13	8275.17
	Mann-Whitney U	5469	1680	15.00	403.0	1762	649

H = horizontal movements; V = up vertical movements; D = down vertical movements; RM = reaching movement; ns = not significant; * = significant; ** = very significant; *** = highly significant; in the pairs of numbers shown as x-y, the first number (x) is the amplitude of the movement and the second one (y) its velocity.

considering the ratio between deceleration and acceleration times. Besides, we estimated smoothness index, introduced for its importance in this field. In fact, it has been used, for example, as a measure of motor performance of both healthy subjects, which usually showed mean values of smoothness index as minimum as possible, and persons with stroke (10, 38), which showed mean values of smoothness also five times greater.

It is important to underline that we have used normalised jerk-based measures in order to characterisethe movement regularity which is related to the shape of the movement trajectory. In particular, normalized jerk values have been computed in order to infer on the changes of the movement's "shape" for different set of reaching movements, performed by healthy subjects with different velocity and amplitude.

Results here obtainedshow that values of all indexes are close to the values of the indexes that we expect in a theoretical motor behaviour (one for symmetry, the minimum possible value for smoothness, zero for skewness and three for kurtosis)in according with the minimum jerk theory. This is not so surprising, since this preliminary study has involved only healthy subjects, for which holds the hypothesis thatthe phases of acceleration and deceleration are characterized by similar time periods and the movements are as more regular as possible. However, although the values obtained do not differ greatly from those expected, significant differences among different types of RM (different direction, amplitude and velocity) can be observed, so allowing to highlight the potentiality of the methodology. In particular, it is possible to point out the followings findings.

In general, the smoothness index is resulted to be more sensible to variations in all movement's characteristics. Changes in its value, in fact, are very often significant either by changing the type of movement (horizontal or vertical), either by varying the values of amplitude and velocity.

This is also in according with a preliminary study in which the authors have addressed in details the relationships of the kinematic indexes with amplitude and speed of the movement. Particularly, among all kinematic indexes, the smoothness index showed the higher correlations' values, following an exponential growth relationship both with velocity and amplitude in horizontal and vertical reaching movements (30).

Besides, at low amplitude values and as the speed increases, the movement becomes more regular (the smoothness decreases significantly) and the velocity profile more symmetrical (please refer to symmetry and skewness indexes), even if flatter with respect to a Gaussian curve (kurtosis index moves away from the characteristic value of 3).

It should be noted that the minimum jerk trajectory describes how a system should move from rest to a target location in a desired time. The minimum-jerk model predicts symmetric, bell-shaped velocity profiles both in single-joint and multi-joint movements and assumes that movements start and end at full rest. The smoothness values in these conditions are expressed by the value 360 D^2/T^5, where D is the final position of the arm and T is the time elapsed. However, it is difficult to compare a real (experimentally measured) movement to its equivalent minimum-jerk trajectory because the exact start and end times and positions of real movements are usually not zero. Hence, it is important to define a range of minimum values of smoothness in real conditions.

Our results, obtained in real conditions (ranging between 115 and 539), having the same order of magnitude of the value expected in theoretical conditions, can be considered as an useful starting point for define a normality range of smoothness.

Moreover, despite the minimum jerk theory predicts movement trajectories with bell-shaped symmetric velocity profiles, when an higher accuracy of target acquisition is required or when the velocity of the movement is imposed the velocity profiles can be somewhat asymmetric (39, 40). In fact the jerk minimization holds the hypothesis that movements start and end at full rest without considering that a single-joint RM usually can be characterized by a certain amount of overshoot.

According to this consideration, although we noted a high degree of symmetry of the velocity profiles, as expected, kinematic indexes' values are not perfectly overlapped with the theoretical ones, especially for slower movements as already shown in previous works (41, 42).

In conclusion, symmetry and smoothness indexes allow the evaluation of the regularity of upper arm reaching single-joint movements, in healthy subjects during RMT, and kurtosis and skewness allow to quantify the adaptation of the velocity profile to a Gaussian curve.

However, although the measures of skewness and symmetry give us the same information of "the lack of symmetry" of the velocity profile, the skewness index shows a higher variability (the high standard deviation means that there is a large variance between the data and the mean value); so, in future works, we could use only the coefficient of symmetry.

This findings show the important of these parameters in defining the *movement quality* according to the minimum jerk theory so, starting from these results obtained on healthy subjects, future studies will assess the quality of patient's movement in robot-assisted rehabilitation. Particularly, we will focus on the shoulder rehabilitation since up to now robotic rehabilitation studies of the upper extremity have generally focused on stroke survivors leaving less explored the field of orthopaedic shoulder rehabilitation.

In pathological conditions it will be expected more fragmented and less continuous movements, and highly asymmetric velocityprofiles, quite unlike from regular movements. So we expect that this behaviour is also confirmed by the changes of the statistical indexes here proposed, as already seen in patients with rotator cuff disease (43).

Further, a possible extension of the metric used in this work will regard the study of the kinematic quality of the pathological reaching movements by means the submovements theory. The goal of sub-movements extraction is to infer the sub-movements composition of a movement from kinematic data and it gained a great appeal in the rehabilitation field over the last years. It is know that (44) the reaching movements performed by pathological subjects are fragmented, and that these fragments were highly stereotyped in their shapes. Then, these movements become smoother as recovery proceeds and this was attributed to a progressive overlapping and blending of submovements. According to this theory, the authors have already showed preliminary results on the evaluation of the kinematic *quality* (45) and the motor composition of visually-guided reaching movements from people with Parkinson's Disease applying a sub-movements decomposition method.

Because of the simplicity of the motor tasks, we do not expect great differences between movements performed by young people (about forty-year-old subjects) and healthy older people (for example seventy-year-old subjects). However, as now specified in the manuscript, this topic will be investigated in future works.

Finally, except for the smoothness, differences in indexes values obtained for horizontal movements, i.e. at constant gravity, are not significant whereas they are often significant in vertical movements. This result could be due to the effect of gravity. To study this effect in more detail, we are planning to use the light-G compensation mode. In the system used, in fact, each MJS axis is equipped with a completely independent force control and adjustment unit allowing a light-G compensation mode which can totally cancel the weight of the arm making the shoulder joint completely "lightened" experiencing a perceptive exploration at "no-load".

Appendix A. Complete results of the statistical analysis

All the results of the statistical analysis were considered not statistically significant (ns) if $p > 0.05$.

Besides, we used * if $p< 0.05$ (significant); ** if $p< 0.01$ (very significant); *** if $p< 0.001$ (highly significant).

In all tables, in the pairs of numbers shown as x-y, the first number (x) is the amplitude of the movement and the second one (y) its velocity.

The Kruskal-Wallis test have been used to test differences in indexes values due to different amplitude and velocity (but with the same type of movement), involved always 6 groups and considered the Gaussian approximation (Table VI).

In order to test differences in indexes values correlated to the type of movement (at fixed amplitude and velocity). We used the Mann Whitney test (Gaussian approximation. two-tailed). Since the differences in the other indexes were significant in a random way (which has to be further deepened), for sake of brevity, only results concerning the smoothness are shown (Table XI).

The following symbols are used:
H for horizontal movements
V for up vertical movements
D for down vertical movements

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