Synergies and end-effector kinematics in upper limb movements

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THE EFFECT OF THE HEIGHT TO WHICH THE HAND IS LIFTED ON HORIZONTAL CURVATURE IN HORIZONTAL POINT-TO-POINT MOVEMENTS

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Abstract

In point-to-point reaching movements, the trajectory of the fingertip along the horizontal plane is not completely straight but slightly curved sideward. The current paper examines whether this horizontal curvature is related to the height to which the finger is lifted. Previous research suggested that the height to which the hand is lifted might be a determinant of horizontal curvature. We asked participants to make point-to-point movements in three conditions: constrained movements (i.e., fingertip keeps contact with table-top) over vertically curved surfaces that differed in height, constrained movements over a flat surface, and unconstrained movements (i.e., fingertip lifted from table-top). In constrained movements we found a strong relation between horizontal curvature and lifted height of the finger. Interestingly, for unconstrained movements, the relation between horizontal curvature and height to which the finger was lifted was weak. This demonstrates that the height to which the finger was lifted relates to horizontal curvature in some, but not in all conditions. This suggests that the height to which the hand is lifted should be included, in particular for constrained movements, when giving a full account of horizontal curvature in point-to-point movements.

Introduction

It is generally known that in point-to-point reaching movements the trajectory of the fingertip in the horizontal plane is not completely straight but slightly curved sideward (so-called, horizontal curvature; see [6,7,57–59]). In addition, it has been repeatedly reported that this horizontal curvature is smaller for constrained movements, where the fingertip is constrained to the table top, than for unconstrained movements, where the fingertip is lifted from the table-top [6,7,57–59]. The fact that constrained and unconstrained movements differ in horizontal curvature and in the lifting of the hand (cf. [6]) suggests a relation between curvature and the height to which the hand is lifted. The current paper examines this relation, both in constrained and in unconstrained movements.

Several factors explaining the origins of horizontal curvature have been identified. Some of these factors can be clearly attributed to planning, for instance, the instruction to move straight caused point-to-point movements to be performed more straight [58]. In addition, vision has been shown to influence horizontal curvature [59,103]. Furthermore, haptic misperception of movement direction has been shown to increase the amount of horizontal curvature [104]. However, for other factors affecting horizontal curvature it is not so clear from where they originate. For instance, it is unclear to what extent the finding that horizontal curvature was larger for movements from left to right than for forward movements [6,57,105], or that horizontal curvature relates to movement speed [106], stems from planning or from biomechanics. Moreover, the phenomenon that horizontal curvature was larger in unconstrained movements compared to constrained movements led Desmurget and colleagues [7,57] to propose that these movements were planned in different spaces (joint space vs. Euclidian space). This instigated a discussion of whether this difference is related to the space of movement planning or to other differences between these movements. Evidence for the latter position came from Bongers and Zaal [6] who showed that horizontal curvature is larger for constrained movements performed over a vertically curved surface than over a flat surface. This finding demonstrated that horizontal curvature could be invoked in constrained movements, making the explanation of Desmurget and collegues [57] in terms of planning space unlikely.

The finding of Bongers and Zaal [6] suggests that the larger horizontal curvature of unconstrained movements may be related to the height to which the hand is lifted. However, from their results it remained unclear whether lifting of the hand per se results in horizontal curvature, or, alternatively, horizontal curvature scales with the height to which the hand is lifted. Establishing the relation between horizontal curvature and the height to which the hand is lifted in a point-to-point movement is the key goal of the current paper. To do this we used three conditions of horizontal point-to-point movements in our experiment; constrained movements over vertically curved surfaces that differed in height, constrained movements over a flat surface, and unconstrained movements. Each of these movements was executed in one of three movement directions, to examine workspace effects [6,7,105]. We focused on two questions: 1) Does horizontal curvature gradually increase when the hand has to be lifted systematically higher in constrained movements, and 2) Does a relation exist between the height to which the finger was lifted and horizontal curvature within unconstrained movements.

Methods

Participants

Fifteen right-handed participants (8 male and 7 female, mean age 21.3 years; standard deviation 1.07 years) with normal or corrected-to-normal vision participated. The participants gave informed consent before the start of the experiment. The study was approved by the University Medical Center Groningen, Center for Human Movements Sciences local Ethical Board.

Materials

Five different surfaces (Figure 1) were used to systematically vary height. The surfaces were constructed from plates (50 x 20 cm) covered with black PVC. The 0 cm surface was flat and all curved surfaces were constructed as segments of different cylinders that were cut in such a way that the distance between the cuts was always 30 cm and the peak heights were 1.5, 3.0, 4.5, or 6.0 cm. All five surfaces could be attached to a board, so that the direction of the surfaces could be adjusted to create three different movement directions (0°, 45° and 90°), as shown in Figure 2.

The movements were measured with two Optotrak 3020 system (Northern Digital, Waterloo, Canada) sensors. Six rigid bodies, made of PVC, with each three markers, were attached to the sternum, the acromion, at the left side of the right upper arm below the insertion of the deltoid, proximal to the ulnar and radial styloids, the dorsal surface of the hand [67] and to the index finger [43]. A small plate was taped under the index finger to prevent the finger from flexing in the proximal interphalageal and the distal interphalangeal joints. A standard pointer device was used to link the markers to 19 local anatomical positions as stated in Van Andel et al. [67].

Figure 1. The five surfaces used in the experiment.

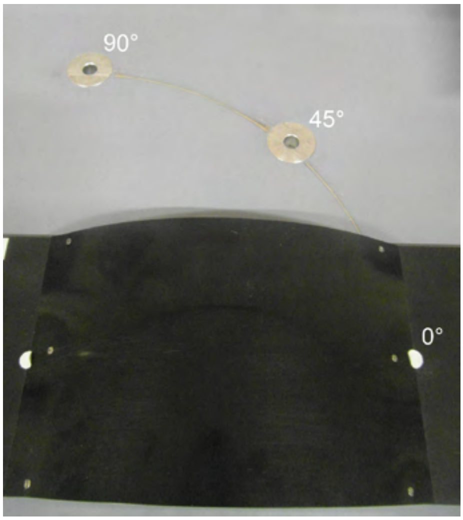

Figure 2. The plate onto which the surfaces could be attached in the three directions.

Procedure and design

The board onto which the plates with the surfaces could be attached was placed on a table at which a participant sat on a chair. The back of the chair was extended with a plate to which the trunk of the participant was gently strapped to prevent movements of the trunk and keep the shoulder at the same position in space [43]. At the beginning of each trial the elbow was held against a stand to keep the starting posture as equal as possible across all conditions. When movement commenced the movements of the wrist and elbow were not restricted. Each trial started with the fingertip on the start location (i.e., a dot on the plate). Following a beep produced with E-studio (version 1.1) participants performed a reaching movement from the start location to the end location (i.e., the second dot on the plate). Participants were instructed to perform the movements as fast and accurate as possible. In the unconstrained conditions the fingertip had to be lifted from the surface. In the constrained conditions the fingertip needed to stay in touch with the surface; no restraints to other joints or body parts were applied. The experimenter could change the five surfaces (unconstrained on 0 cm and constrained on 0, 1.5, 3, 4.5, or 6 cm) and the three movement directions (left to right (0°), diagonal (45°) and forward (90°)), to create 18 movement conditions. The 18 movement conditions were presented 30 times in blocks of which the order was randomized. Each participant performed a total of 540 movements. The start of the movements was at the same location for all movement directions and the movements were always away from the body.

Data analysis

The start and the end of the movement were determined by searching forward and backward, starting from the peak velocity, to the first data point where the velocity reached a threshold of 25 mm/s. Of the total of 8100 recorded trials, 162 trials were removed due to inadequate detection of start or end of movements (the velocity did not fall below the threshold when participants returned too fast to the starting location), technical problems (markers were not always visible to the sensors), or movements that did not match the intended movement conditions[1]. Horizontal curvature was defined as the maximum absolute distance between the projection of the movement trajectory onto the horizontal plane and the line connecting the start and endpoint (cf. [6,7,57]). Lifted height was defined as the maximum height to which the fingertip was lifted. Apart from horizontal curvature, we looked at kinematic differences between the movement conditions; movement time symmetry index of velocity and peak velocity were computed. Symmetry index of velocity was defined as the time needed to reach peak velocity divided by movement time. Peak velocity was defined as the maximum value of the velocity between beginning and end of the movement. The data analysis was performed in MATLAB (Mathworks, Natick, MA).

All statistical analyses were executed using SPSS software (IBM, Armonk, New York). We commenced by analyzing the effect of the height to which the hand is lifted on horizontal curvature in constrained movements; preplanned polynomial contrasts were tested with a

1 Due to mistakes in data collection a total of 4 movement conditions of different participants were incorrect. These missing values were replaced using the EM procedure in SPSS that estimates the means, the covariance matrix, and the correlation of variables with missing values, using an iterative process. The missing conditions were: participant 6, direction 90°, surface height 3.0 cm; participant 10, direction 0°, surface height 3.0 cm; participant 11, direction 90°, unconstrained; participant 14, direction 90°, surface height 4.5 cm.

repeated measures ANOVA. The ANOVA was executed with surface height (0, 1.5, 3, 4.5, and 6 cm) and movement direction (left to right, diagonal and forward) as within-subject factors.

Second, we examined the relation between the horizontal curvature and the height to which the fingertip was lifted in unconstrained movements. For each individual participant and direction we computed the range of the maximum height to which the fingertip was lifted and the range of horizontal curvature. We computed the correlation between horizontal curvature and height to which the fingertip was lifted for each movement direction separately. To investigate whether the shape of the trajectory of the lifting of the hand in unconstrained movements had a curved shape (i.e., a similar as the constrained movements over a vertically curved surface), we performed a repeated measures ANOVA. The ANOVA was executed with percentage of movement (1%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% and 100%) and movement direction (left to right, diagonal and forward) as within-subject factors.

Third, the horizontal curvature between unconstrained movements and constrained movements over a straight surface was compared. A repeated measures ANOVA was performed with movement condition (unconstrained vs. constrained over straight surface) and direction (left to right, diagonal and forward) as within-subject factors.

Fourth, the effects of surface curvature on kinematic variables were established with analyses that we did on horizontal curvature with preplanned polynomials of surface height and movement direction. This analysis was performed on movement time, symmetry index of velocity and peak velocity.

To understand the significant effects of the ANOVA's, generalized eta-squared was used to calculate effect size. These were interpreted according to Cohen's recommendation of 0.02 for a small effect, 0.13 for a medium effect and 0.26 for a large effect [95]. For effect size of the t-tests Cohen's d was used, which was interpreted according to Cohen's recommendation of 0.2 for a small effect, 0.5 for a medium effect and 0.8 for a large effect [69]. Due to the large number of analyses we used an α of 0.01.

Results

Constrained movements over surfaces varying in height

The ANOVA on horizontal curvature showed that the linear contrast of surface was significant, $F(1,14) = 48.56$, $p < 0.001$, $\eta^2_G = 0.32$, demonstrating that horizontal curvature was larger for constrained movements over a higher vertically curved surface (see Figure 3 and 4). The linear contrast of movement direction, $F(1,14) = 63.74$, $p < .001$, $\eta^2_G = 0.78$, demonstrated that horizontal curvature was larger in the left to right direction than in the forward direction and the diagonal direction. Both linear contrasts were strong effects. Figure 3 and 4 show examples of movement paths and the means and standard errors of the means of horizontal curvature for unconstrained and constrained movements. In these figures, positive horizontal curvature indicated that the maximum deviation from the straight line is above the straight line for left to right movements and left from the straight line in forward movements.

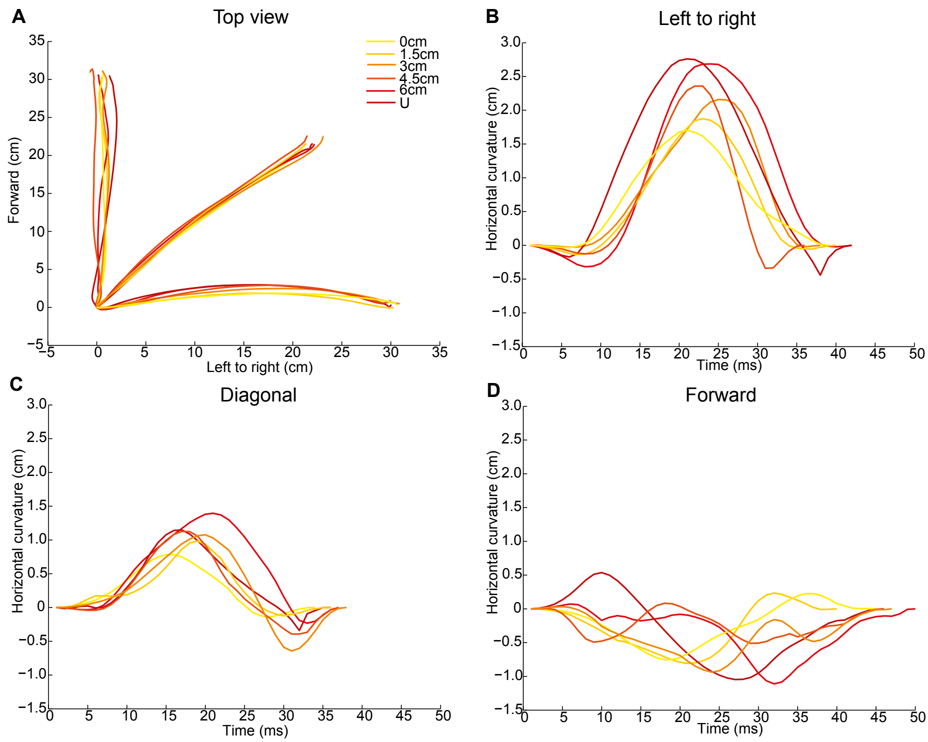

Figure 3. Examples of the behavior in each condition. (A) the projections onto the horizontal plane, and (B-D) horizontal curvature in time, for the same trials as in A. Positive horizontal curvature indicated that the maximum deviation from the straight line is above the straight line for left to right movements and left from the straight line in forward movements.

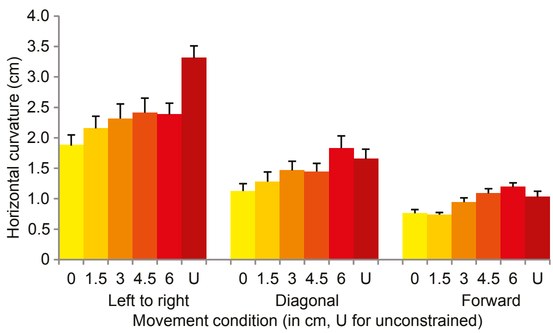

Figure 4. Means and standard error of the mean of horizontal curvature for the different movement conditions of Experiment 1.

Relation horizontal curvature and lifted height for unconstrained movements

The relation between horizontal curvature and the height to which the hand was lifted was very weak or negligible. The correlation coefficients for the analyses on each direction for each individual participant are shown in Table 1. Of the 44 correlations, 5 showed a relation with an r between 0.5-0.75 and 10 showed a relation with an r between 0.25-0.5. The other 29 correlations had an r smaller than 0.25. In short, together this demonstrated that the relation between horizontal curvature and the height to which the hand was lifted was very weak to negligible in unconstrained movements.

To provide further information about the movements of participants in the unconstrained condition, we examined the actual values of the height to which the finger was lifted and the horizontal curvature (see Table 1). The smallest height to which the finger was lifted was 1.09 cm and the largest height was 13.63 cm. The average maximum heights of the unconstrained movements per direction were 4.0 cm (±1.3) for left to right movements, 4.4 cm (±0.8) for diagonal movement and 5.2 cm (±1.4) for forward movements. Furthermore, the percentage of reaches with a lifted height within the range of 0 to 6 cm was 91.3% for left to right movements, 92.3% for diagonal movements and 71.6% for forward movements indicating that our manipulation of surface height for the constrained movements captured for the large part the range of the heights to which the finger was lifted in unconstrained movements. The horizontal curvature ranged from 0.2 cm to 6.1 cm in the unconstrained movements. We also calculated for each participant and movement direction the employed range in height to which was reached and the horizontal curvature over the 30 trials. The ranges in the different directions showed no noteworthy differences, therefore we pooled the data over directions reporting the means, standard deviations and ranges of horizontal curvature and lifted height per participant. The smallest range of the horizontal curvature within one participant was 2.5 cm and the largest range was 5.8 cm. The smallest range of lifted heights was 4.18 cm and the largest range was 11.3 cm. This showed that the range explored was larger for the height to which the fingertip was lifted than for the horizontal curvature.

The analysis on the shape of the trajectory of the lifting of the hand in unconstrained movements showed a strong significant quadratic effect of time, $F(1,14) = 279.27$, $p < 0.001$, $\eta^2_G = 0.91$, demonstrating that the trajectory of the fingertip in unconstrained movements is curved similar to the constrained vertically curved movements (see table 2). Furthermore, this analysis showed a small significant effect of direction, $F(1,14) = 0.28$, $p < 0.05$, $\eta^2_G = 0.14$, demonstrating that in forward movements the fingertip was lifted higher than for diagonal and left to right movements. The small interaction effect between these two contrasts was also significant, $F(1,14) = 10.67$, $p < 0.01$, $\eta^2_G = 0.12$.

Unconstrained movements vs. constrained movements over a flat surface

The analysis on the difference in horizontal curvature of unconstrained movements and constrained movements over a flat surface showed a significant effect of movement condition, $F(2,28) = 102.51$, $p < 0.001$, $\eta^2_G = 0.52$, demonstrating that horizontal curvature was larger for unconstrained movements compared to constrained movements over a flat surface (see Figure 3 and 4, U and 0cm in legend of figures). The significant effect of movement direction, $F(2,28) = 83.61$, $p < 0.001$, $\eta^2_G = 0.80$, demonstrated that horizontal curvature was largest in the left to right direction and smallest in the forward direction. The significant interaction, $F(2,28) = 38.77$, $p < .001$, $\eta^2_G = 0.33$, indicated that the difference in horizontal curvature between unconstrained and constrained movements was largest for the left to right direction and smallest for the forward direction. All effects showed large effect sizes.

Table 1. Correlations, means, standard deviations and ranges (in cm) of horizontal curvature and maximum height to which the fingertip is lifted per participant in unconstrained movements.

	Correlation horizontal curvature and lifted			Horizontal curvature			Lifted height		
P[a]	Left to right	Diagonal	Forward	Mean	SD[b]	Min-Max[c]	Mean	SD[b]	Min-Max[c]
1	r = 0.266	r = 0.15	r = 0.016	1.49	0.97	0.28 - 4.00	3.40	0.94	1.70 - 5.88
2	r = 0.208	r = 0.157	r = 0.188	1.71	1.15	0.25 - 4.26	5.44	1.93	2.36 - 13.63
3	r = -0.160	r = -0.065	r = -0.177	1.51	0.74	0.38 - 3.24	5.61	2.14	2.39 - 10.16
4	r = 0.209	r = 0.086	r = -0.164	1.65	0.90	0.36 - 3.31	5.21	1.28	2.36 - 8.56
5	r = 0.029	r = -0.052	r = 0.015	1.25	0.62	0.33 - 2.83	3.34	1.36	1.18 - 7.29
6	r = 0.472**	r = -0.125	r = 0.201	2.41	1.31	0.42 - 5.76	5.33	1.48	2.04 - 11.15
7	r = 0.495**	r = -0.046	r = 0.257	2.36	1.29	0.30 - 5.27	4.83	1.26	1.58 - 8.94
8	r = 0.468*	r = -0.186	r = 0.217	2.03	1.04	0.35 - 4.23	4.86	1.50	1.47 - 8.99
9	r = -0.124	r = 0.611**	r = 0.310	1.80	0.97	0.46 - 4.13	3.67	1.31	1.09 - 6.60
10	r = -0.055	r = 0.198	r = 0.119	1.89	1.13	0.29 - 4.04	4.18	0.98	1.73 - 6.61
11[d]	r = 0.735**	r = 0.112	-	2.02	1.19	0.47 - 4.49	4.44	1.35	2.21 - 9.96
12	r = 0.647**	r = 0.596**	r = 0.286	2.78	1.53	0.30 - 6.06	3.85	1.61	1.27 - 9.85
13	r = -0.072	r = 0.365*	r = 0.656**	2.23	1.37	0.20 - 5.38	4.05	1.10	1.59 - 7.34
14	r = 0.497**	r = 0.337	r = -0.295	2.38	1.33	0.32 - 5.25	3.55	1.12	1.33 - 6.16
15	r = 0.324	r = 0.046	r = 0.168	2.56	1.40	0.48 - 5.41	6.31	1.82	3.27 - 12.21

a. P for participant
b. SD for standard deviation
c. Min-Max for minimum and maximum
d. Replacing missing values is not appropriate for correlation analysis, therefore, in the analysis and the descriptive statistics of Table 1 of participant 11 only the left to right and the diagonal direction are taken into account.
* Correlation is significant at the 0.05 level
** Correlation is significant at the 0.01 level

Table 2. Means and standard error of the mean of lifted height at nine points in time.

	Percentage of Movement Time								
Movement direction	**10%[a]**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**
Left to right	0.15 (0.03)	1.08 (0.17)	2.47 (0.26)	3.45 (0.3)	3.79 (0.33)	3.49 (0.33)	2.73 (0.29)	1.73 (0.2)	0.63 (0.08)
Diagonal	0.19 (0.02)	1.1 (0.09)	2.6 (0.15)	3.76 (0.19)	4.12 (0.22)	3.74 (0.21)	2.88 (0.19)	1.73 (0.14)	0.56 (0.05)
Forward	0.25 (0.04)	1.52 (0.18)	3.45 (0.33)	4.7 (0.36)	4.91 (0.32)	4.25 (0.25)	3.15 (0.19)	1.85 (0.15)	0.47 (0.05)

a. The heights at 0% and 100% were left out because they were approximately zero.

Kinematics

The means and standard errors of the means of movement time, symmetry index of velocity, and peak velocity for the different movement conditions are shown in Table 3.

Movement time.

The linear contrast of surface was significant, $F(1,14) = 42.389$, $p < 0.001$, $\eta^2_G = 0.54$, demonstrating that movement time was longer for constrained movements with a higher vertically curved surface. The quadratic contrast of movement direction, $F(1,14) = 199.4$, $p < .001$, $\eta^2_G = 0.77$, demonstrated that movement time was longer for left to right and forward movements compared to diagonal movements. Both contrasts were strong effects.

Symmetry index of velocity. The linear contrast of surface was significant, $F(1,14) = 18.807$, $p = 0.001$, $\eta^2_G = 0.43$, demonstrating that the peak velocity occurred later in the movement when the vertically curved surface was higher. The linear contrast of movement direction, $F(1,14) = 105.234$, $p < .001$, $\eta^2_G = 0.77$, demonstrated that the peak in velocity occurred later in left to right movements compared to forward movements. Both linear contrasts were strong effects. The linear linear interaction between the effects was significant, $F(1,14) =$

22.888, $p < .001$, $\eta^2_G = 0.3$. This strong interaction effect indicated that for lateral and diagonal movements the symmetry index differed for a larger range over the surfaces whereas it was rather constant for the forward movements.

Peak Velocity. The strong linear contrast of direction was significant, $F(1,14) = 40.01$, $p < 0.001$, $\eta^2_G = 0.63$, demonstrating that peak velocity was lower for forward movements compared to diagonal and left to right movements.

Table 3. Means and standard error of the mean of movement time and symmetry profile of velocity for every movement condition separate of Experiment 1.

		Surface (cm)					
	Surface (cm)	**0**	**1.5**	**3**	**4.5**	**6**	**U[a]**
MT[b] (s)	Left to right	0.474 (0.021)	0.452 (0.018)	0.474 (0.019)	0.475 (0.021)	0.502 (0.019)	0.439 (0.02)
	Diagonal	0.421 (0.025)	0.431 (0.022)	0.439 (0.02)	0.449 (0.017)	0.479 (0.018)	0.418 (0.014)
	Forward	0.509 (0.022)	0.528 (0.027)	0.56 (0.028)	0.56 (0.032)	0.588 (0.028)	0.478 (0.02)
SIV[c]	Left to right	0.505 (0.012)	0.538 (0.013)	0.558 (0.012)	0.57 (0.015)	0.591 (0.012)	0.471 (0.014)
	Diagonal	0.463 (0.01)	0.482 (0.01)	0.504 (0.01)	0.487 (0.012)	0.515 (0.014)	0.402 (0.01)
	Forward	0.462 (0.009)	0.484 (0.011)	0.478 (0.008)	0.477 (0.014)	0.47 (0.014)	0.391 (0.012)
PV[d] (cm/s)	Left to right	126.92 (6.43)	137.72 (7.06)	137.19 (8.09)	135.92 (8.54)	134.4 (7.2)	152.63 (7.08)
	Diagonal	150.79 (8.67)	144.29 (7.94)	144.16 (7.9)	138.73 (76.26)	138.44 (6.67)	159.72 (7.63)
	Forward	119.02 (4.88)	114.04 (5.31)	114.86 (6.33)	112.05 (6.25)	111.94 (5.59)	137.57 (5.65)

a. U for unconstrained movement.
b. MT for movement time.
c. SPV for symmetry index of velocity
d. PV for peak velocity

Discussion

We studied whether a relation exists in horizontal point-to-point movements between horizontal curvature and the height to which the finger is lifted. To study this relation we used three conditions of horizontal point-to-point movements in our experiment; constrained movements over vertically curved surfaces that differed in height, constrained movements over a flat surface, and unconstrained movements. We found a strong relation between horizontal curvature and the height to which the hand is lifted in constrained movements but we found in most cases a very weak relation in unconstrained movements.

Previous studies have implicated several factors that contribute to the horizontal curvature of point-to-point movements. One such factor is the height to which the hand is lifted, as proposed by Bongers and Zaal [6]. Our study revealed a strong relation between horizontal curvature and the height of the surface over which a constrained movement is performed. This finding implies that height to which the finger is lifted is a determinant of horizontal curvature in constrained movements suggesting it should be part of a conclusive account of horizontal curvature. Because there is a systematic relation between horizontal curvature and the height to which the hand is lifted, it seems unlikely that the differences in curvature originate from differences in the reference frame in which constrained and unconstrained movements as hypothesized in earlier studies (cf. [7]). Our data imply that this relation stems from factors related to the height to which the hand is lifted.

Importantly, the relation between horizontal curvature and lifted height did not show up for unconstrained movements; the correlations between these two variables were generally small. Only in few cases we found correlations that were weak to moderate (r between 25-75%); most of the correlations indicated that the relation of the height of lifting and horizontal curvature was negligible in unconstrained movements (r lower than 25%). Note that the variation in height and the variation in horizontal curvature were large enough to reveal a relation between curvature and lifted height (see Table 1). Hence, the range of the variation in either variable could not explain that we did not find a correlation. Interestingly, the trajectories of unconstrained and constrained movements over a vertically curved surface had a shape that was similarly vertically curved.

For unconstrained movements, the average height to which the finger was lifted fell in the middle range of our manipulations of height of the surface over which constrained movements were performed. But note that the range in height to which the finger was lifted was much larger for unconstrained movements than the range in which we manipulated surface height of constrained movements. Thus, although the range of variation in height to which the finger was lifted was larger in unconstrained movements than in constrained movements, we found no relation between horizontal curvature and height to which the hand and finger were lifted in unconstrained movements whereas in constrained movements this relation was strong.

Our last result on curvature confirmed earlier findings that horizontal curvature is larger for unconstrained movements than for constrained movements when moving over a straight surface [6,7,57–59]. We found that this effect was largest for the left to right direction and smallest for the forward direction, in line with other reports [6,7,57]. The differences in horizontal curvature among the three movement directions deserve further attention, in particular for unconstrained movements. Our results indicated that the mean maximum height of unconstrained movements from left to right was smaller than that of forward unconstrained movements. Interestingly, horizontal curvature was larger for left-to-right movements than for forward movements (cf. [6,105,107]). The effect of movement direction on horizontal curvature suggests biomechanical factors playing out in horizontal curvature. This suggestion is inspired by what we saw in the movements of the arm; casual observations during the experiment indicated that vertical elbow movement was minimal in left to right movements whereas this was considerable in forward movements. To quantify this difference over movement directions we computed the difference in vertical elbow position between the beginning and end of the movement for the separate movement directions for all movements. For left to right movements this displacement was 0.2 cm, for diagonal movements 3.2 cm, and for forward movements 6.7 cm. How such differences in arm movement might lead to differences in horizontal curvature over movement directions is beyond the scope of the current paper.

We examined kinematics of the point-to-point movements demonstrating that moving over a curved surface changed the kinematics of the movement. Most of these findings can be related to other literature [6,108]. Diagonal movements had the smallest movement time, which was also found by Gordon and colleagues [108] who claimed that this was due to inertia of the arm, which is lowest in the diagonal direction. Unconstrained movements were executed faster than constrained movements probably due to the lack of friction in unconstrained movements [6]. Movement time was longer when the vertically curved surface was higher, presumably resulting from a longer trajectory. Furthermore, the analysis on symmetry index of velocity showed that peak velocity was reached later when the vertically curved surface was higher. Peak velocity also occurred later in left to right movements compared to forward movements. Peak velocity was lower for forward movements compared to diagonal and left to right movements. Diagonal movements had the highest peak velocity, which might also be due to the inertia of the arm [108]. These results showed that the vertically curved surfaces slightly changed the kinematics of the movement in ways that could be expected from the manipulations.

In conclusion, horizontal curvature in point-to-point movements seems to relate to the height to which the hand and finger are lifted. However, this relation clearly shows up in constrained movements and not in unconstrained movements. This suggests that the height to which the hand is lifted should be included, especially regarding constrained movements, when giving a full account of horizontal curvature in point-to-point movements.