Organization of Goal-Directed Action at a High Level of Motor Skill: The Case of Stone Knapping in India

E.V. Biryukova and B. Bril

We analyzed the relationship between goal achievement and execution variability in craftsmen who have acquired the highest “ultimate” skills of stone knapping. The goal of a knapping movement is defined as the vector of the final velocity of a hammer, crucial for detaching a flake and, consequently, for the shape of the final product. The execution of the movement is defined by the kinematic pattern of the arm (i.e., by the coordination between the joint angles corresponding to the seven arm degrees of freedom). The results show that (a) the direction of final velocity is very stable for all craftsmen, whereas the amount of kinetic energy transmitted to the stone was craftsman specific and (b) the kinematic pattern of the arm was strongly individual and was a reliable sign of the level of skill—the highest level was characterized by the highest flexibility of movement kinematics. We stress the importance of conducting the experiment in natural conditions for better understanding of the relationship among the purpose (the final shape of the stone), the goal, and the execution of the movement.

Keywords: multijoint kinematics, flexible synergy, natural task conditions

How does the desire to perform a goal-oriented action give rise to the execution of a sequence of adapted movements? Considering this question, N.A. Bernstein (1991/1996, p. 274/234) recommended learners “to concentrate one’s whole attention on the quality of the movement outcome, not only at the beginning of training a skill, but also during the later phases, when the skill is ‘perfect’ (how will it ever be possible to say that perfection has been reached?). One must concentrate on the what of the movement, the hows will come later by themselves.” Besides the questions of the what and the how, a third, equally important question—to what purpose—must be answered for an adequate understanding of human goal-directed motor actions. This question is closely related to the conception of the anticipated model of the needed future, which underlies the Bernsteinian “physiology of activity” (Bernstein, 1965, 1966, 1967).

Most studies on movement control consider actions such as pointing, reaching, or grasping, which concern the what and the how. When reaching or pointing is
considered, the *what* relates to the positioning of the digits in the prescribed location in three-dimensional space or to the achieving of the desired configuration of the fingers, whereas the *how* usually relates to the coordination of the different degrees of freedom (DoFs) of the limb. In using minimally challenging task conditions, these studies underrate the contextual aspects of the movement and thus avoid the question of goal-directed action and purpose. In everyday life settings, however, once the goal has been established, there are, in theory, many alternatives on how to achieve the ultimate goal. This is especially true for labor movements, which often involve tool use. The constraints imposed by the tool and the strong reliance on external information make these life settings the most suitable situations to study the execution and completion of a goal-oriented action in regard to the control of posture and movement.

Interestingly, in the early 20th century, the pioneering works of Bernstein (Bernstein, 1923, 1924a, 1924b, 1924c, 1934, 1947) that dealt with labor movements resulted in the formulation of the principles of his “physiology of activity” (Bernstein, 1965, 1966, 1967). Widely discussed before Bernstein by Marey (1868), Sechenov (1904), Gilbreth and Gilbreth (1909), and Demenÿ (1924/1993), tool use has, since then, been neglected by physiologists and psychologists. When investigating the principles of motor control, experimental studies generally concentrated on relatively simple actions because labor movements were probably regarded as too complex. Surprisingly, this domain has been recently revived by primatologists and archaeologists investigating the convergent evolution of tool-using abilities in human and nonhuman primates (for a review see Roux & Bril, 2005). A previous interdisciplinary study of stone knapping in India (Roux, Bril, & Dietrich, 1995; Bril, Roux, & Dietrich, 2000) suggested that craftsmen’s tool use presented the ideal situation to investigate the relationship between a goal-oriented action and its completion.

We present here an analysis of the hammering movements of Indian craftsmen, whose high-level expertise stands for the “ultimate” stage of learning. As was suggested in the previous studies, a prerequisite to expertise is to be found in the ability to finely tune the elementary functional movement, which ends with the detachment of an appropriate flake, to its goal (Roux et al., 1995; Bril, Roux, & Dietrich, 2005). Focusing on the analysis on the elementary stroke, we investigate the relationship between the three questions of the *what*, the *how*, and the *to what purpose*. The question *to what purpose* concerns the final shape that the raw material must be given through the knapping process. The question of the *what* refers to the functional goal of a stroke (i.e., the appropriate vector of velocity at the time of contact necessary to detach the desired flake). The question of the *how* is related to the way these craftsmen make use of the redundant number of DoFs of the upper arm to achieve the functional goal of the stroke.

A further complexity of the stone-knapping task lies in the fact that its ultimate goal, the desired shape of the stone, occurs only after a long sequence of stroke movements. The failure of any one of these movements can lead to the failure of the entire task. This complexity requires the highest possible exploitation of an individual’s motor resources. Consequently, the question *to what purpose* appears to be closely related with the question *how*. The goal of our analysis is to reveal the interindividual differences in kinematic patterns, as well as their common features, inherent to the high level of mastery of the skill. In that respect, we follow the
tradition of developmental studies emphasizing individual solutions to movement (Thelen, 1990).

We argue here that the study and the comprehension of high-level skills need to be conducted under the natural conditions in which the movement was acquired. Thus movement recordings must be made, whenever possible, in the craftsmen’s natural environment (i.e., in the present case, directly in the workshop). Our goal was to study the properties of high-level motor skill without imposing artificial constraints. Thus, we did not impose any particular movement constraints as is usually done in controlled laboratory experiments; the craftsmen were free to choose their initial postures and their individual grip of the hammer, and no special instruction was given for movement execution. As mentioned earlier, we point out the importance of not averaging the parameter values over several participants because the interindividual differences are the key to the understanding of highly skilled movements.

Using the data from the four electromagnetic sensors placed on the hand, the forearm, the upper arm, and the scapula, we have reconstructed the arm kinematics in the form of angular rotations corresponding to the seven DoFs of the arm: flexion-extension and abduction-adduction in the wrist; flexion-extension and pronation-supination in the elbow; and flexion-extension, abduction-adduction, and rotation in the shoulder. We discuss here different aspects of joint-angle coordination (joint-angle amplitudes, contributions, and mutual compensations) and their relation with the variables important for the success of the stroke (the vector of final velocity), as observed in highly skilled craftsmen. We suggest that fine-tuning of visco-elastic properties of the arm joints, and thus controlling the visco-elastic properties of the hammer trajectory, could be a mechanism leading to a successful stroke. We conclude that the kinematic pattern is a reliable sign of the level of skill; the highest level was characterized by the highest flexibility.

Method

Experimental Setting and Participants

**Description of the Knapping Technique.** Manufacturing hard stone beads requires the mastery of a very specific knapping technique, based on the specific properties of the raw material (i.e., cornelian stone). Cornelian, like other fine grain minerals, breaks along a conchoidal fracture, which describes the ways brittle material breaks. Minerals such as quartz and flint, as well as glass, exhibit conchoidal fracture. The fracture is characterized by a smooth and curved fracture surface. More importantly, however, is that conchoidal fracture may be controlled. That is, given the proper configuration of the core surface, the properties of a flake—length, thickness, and width—are determined by direction, velocity, and location of the point of contact (Dibble & Pelcin, 1995; Pelegrin, 2005). This mechanism of fracture has been widely used for stone tool manufacturing.

The knapping technique considered here has been described as an indirect percussion by counter-blows (Pelegrin, 1993). The craftsman, sitting on a rug on the ground in a very constrained cross-legged position (as described later), uses two tools jointly (Figure 1):
• a sharp-pointed iron bar about 50 cm long and 2 cm thick, stuck obliquely into the ground in front of him, and

• a buffalo-horn hammer mounted on a thin wooden stick. Depending on the task, the weight of the hammerhead is usually between 18 g and 40 g; the handle is approximately 35 cm long and weighs less than 10 g.

With one hand, the craftsman holds a piece of stone between his fingers and places the edge of the stone against the pointed tip of the iron bar. With his other hand, he strikes the piece with the hammer so that a flake is detached from the point of contact with the iron bar.

To produce a bead of a specific shape, a large number of flakes of different shapes and different dimensions must be detached always with the same technique. The specific shape and size of a flake are determined by the succession of specific operations on the stone: the processing of the edges (Figure 2a), followed by the ends preparations (Figure 2b), and the so-called fluting movements or axial removals of the crest from the end (Figure 2c). The flutings are the most important step for achieving a final ellipsoidal shape.

Figure 1 — Typical posture of craftsman during stone knapping. The STS sensors are located (1) on the hand, (2) on the forearm, (3) on the arm, and (4) on the acromion. The stationary system XYZ (5) is located on the ground. The axes of independent rotations in the joints are shown: abduction-adduction (Ab-Adw) and flexion-extension (F-Ew) in the wrist, pronation-supination (P-Se) and flexion-extension (F-Ee) in the elbow, and abduction-adduction (Ab-Ads), flexion-extension (F-Es), and rotation (Rots) in the shoulder. Note. Adapted from Roux, 2000.
Participants. The experiment was held in a workshop assigned to our research group for the entire duration of the experimentation. The workshop was located in Khambhat, a small Gujeraty town, in southwest India.

Six expert craftsmen took part in the experiments. For their living, they manufacture high-quality beads, and the duration of their apprenticeship period is approximately 10 years. At the time of the experiment, they had between them an average of about 25 years of practice.

All the craftsmen in the study volunteered, and for their participation they were paid the highest rate for 1 day’s work. They gave their verbal agreement to participate in the study to the owner of the workshop, who hosted the experiment. No written consent was demanded because this does not meet local tradition in which a written agreement would have been considered as a lack of trust.

The craftsmen are referred to in the following by the first two letters of their first name (AB, HA, HU, IN, RA, YO). Although all craftsmen are socially recognized as highly qualified experts, there are some differences between them. IN is considered to be the greatest expert, not only by the salesmen, but also by the Indian government. He is able to make all kinds of shapes in any dimension. The participants RA and YO produce beads of a somewhat lower quality than the others. AB’s specialty is a particular shape of bead, and it is the one examined in our experiments. For more details, see Bril et al. (2000).

Equipment

Video Cameras. The entire session was recorded by two video cameras positioned in front of the craftsman, with an angle of approximately 120 degrees.

Accelerometer. An uniaxial accelerometer with a range of ±250 g (g = 9.8 m/s²), sampling frequency at 240 Hz (natural frequency 3,100 Hz), and an accuracy of ±0.2 m/s² was used to assess the movement of the hammer. It was attached to the opposite end of the hammerhead (i.e., the one not striking the bead—unused end). The sensor signaled the acceleration of the hammer along its trajectory.

Spatial Tracking System. A Spatial Tracking System (STS-Polhemus) was used to record the arm movements. This system uses an electromagnetic field to determine the three-dimensional positions and orientations of the sensors relative to
the stationary system (denoted by 5 in Figure 1). Three Euler angles of rotation of sensor reference frames relative to the stationary system are used to determine the sensor orientations: azimuth $\Psi_{az}$, elevation $\Psi_{el}$, and rotation $\Psi_{ro}$.

The four sensors operated at an acquisition rate of 30 Hz. The static accuracy of the STS system was 0.08 cm RMS for the sensor positions and 0.15º RMS for the sensor orientations. Calibration measurements showed that the system was accurate within 0.7 m of the origin of the stationary system.

The data from the accelerometer and the STS were synchronized during movement recording.

**Experimental Protocol**

Participants sat on a rug in their preferred sitting posture. All of them used the posture illustrated in Figure 1, a posture that makes for a very stable position of the body and of both arms. In certain participants the hammering arm embraces the knee, thus introducing an additional constraint, a kind of pivot at the level of the elbow.

The task consisted of performing the three main operations (Figure 2) necessary to produce an ellipsoidal shape, starting with a 6 cm $\times$ 2.5 cm $\times$ 2.5 cm parallelepiped piece of raw material. A session consisted of knapping a series of five samples of beads. We used three tool conditions (with a normal hammer, with a heavier hammer, and one with a shorter handle) and two raw materials (stone and glass). Thus, each craftsman had to knap 30 beads. In this article we will focus on the normal hammer condition using glass as the raw material. This choice was based on the fact that whereas cornelian stone can differ in hardness and homogeneity, glass does not. Glass, however, has overall similar properties and, thus, provides the same basic conditions for all craftsmen, an important factor for our experiment. In our experiment, the hammer had the following properties: weight of hammerhead = 22 g, handle length = 35 cm, handle weight = 7 g. The craftsmen were instructed to knap an ellipsoidal bead and to take their time to produce a bead of superior quality. The instructions were given in Gudjerati, the language spoken in that region of India.

**Experimental Setup**

1. **Normal Condition Series.** The four sensors of the STS used to record the movement of the hammering arm were firmly attached with adhesive tape to the hand, the forearm, the arm, and the scapula of the participants (Figure 1).

   The locations of the sensors for the movement recordings were chosen to minimize their displacement relative to the arm segments. They were placed (1) on the dorsal surface of the hand; (2) on the dorsal surface of the forearm, approximately 10 cm from the wrist joint; (3) on the dorsal surface of the upper arm, approximately 15 cm above the trochlea humeri; and (4) at the highest point of the acromion (Figure 1). All sensors were within a 0.7-m sphere of the stationary system to ensure acceptable accuracy of the STS.

   The craftsmen reported that the sensors were not a hindrance.

2. **Model Series.** An additional series was recorded to calculate the three-dimensional coordinates of the hammerhead working point (WP; Figure 4) from STS data so the working point coordinates can be calculated in the reference frame of
the hand sensor. To calculate these coordinates, we placed an additional sensor on the handle and recorded a series of knapping strokes leading to a single bead. The data from hand and handle sensors were used to check whether the handle moved relative to the hand.

3. Passive Rotation Series. The positions and orientations of the axes of rotation in the joints are individual parameters necessary to calculate the joint angles (Biryukova, Roby-Brami, Frolov, & Mokhtari, 2000). To determine them, the passive rotations around the corresponding axes were recorded in all participants immediately following each experimental session, with the sensors in place. The participants were asked to relax their arm and to allow the experimenter to execute sequences of five to eight rotations corresponding to all seven DoFs of the arm (Figure 1). All movements started from a neutral position at the joint. The rotation amplitudes were 0.7 to 0.8 of maximal physiological range. Special care was taken to ensure that only one type of rotation at a time was performed.

Data Processing

Procedure of Data Reduction. First, using video recordings, we identified the elementary striking movements that corresponded to the crest flutings. Table 1 gives the number of flutings analyzed for each craftsman.

Second, we extracted the parts of the STS recordings corresponding to the flutings (Figure 3). Then, using these recordings, we calculated the joint angles and the WP trajectories.

Calculating the Working-Point Trajectory. From the model series we calculated mean values of WP coordinates in the reference frame of hand sensor WPX, WPY, and WPZ and the Euler angles of relative orientations of the hand’s sensor and handle’s sensor $\Psi_{az}$, $\Psi_{el}$, $\Psi_{ro}$ (Table 1). The standard deviations of these values varied little during the period of one sample manufacturing. They were taken as the assessment of the rigidity of the “hand + hammer” system.

WP acceleration, calculated numerically as the second derivative of the length of the WP trajectory (Figure 3, thick line), was then compared with the recorded acceleration of the hammer (Figure 3, thin line) to check data consistency and to identify the timing of stroke impact.

Calculating the Kinetic Energy at Time of Contact and the Direction of the Stroke. The analysis of adjustment of the final shape of the beads during the working operations different from flutings shows that more correcting strokes follow less powerful flutings (Bril et al., 2000). We suggest, therefore, that the size of the flake is related to kinetic energy of the hammer at impact. The kinetic energy transmitted to the stone from the hammer is analyzed below as an index of fluting functionality.

It is equal to $mV_{stroke}^2/2$, where $m$ is the mass of the hammer and $V_{stroke}$ is the WP velocity at the time of contact. The recorded acceleration was calibrated using the fitness of the second derivative of the length of the WP trajectory (Figure 3). $V_{stroke}$ was calculated by the integration of the recorded acceleration. Trapezoidal rule was used for integration, and $V_{stroke}$ was assumed to be equal to zero at the beginning of the movement.
Table 1  Number of Flutings Performed During Manufacturing of Five Glass Samples, Mean Distance Between the Hand’s Sensor and the Working Point of the Hammer ($D_{\text{hand-WP}}$), Coordinates of the Working Point in the Reference Frame of Hand’s Sensor ($WP_x$, $WP_y$, and $WP_z$), and Euler Angles of Relative Orientations of Hand’s Sensor and Handle’s Sensor ($\psi_{az}$, $\psi_{el}$, $\psi_{ro}$), Averaged Over the Period of One Sample Manufacturing

<table>
<thead>
<tr>
<th>Craftsman</th>
<th>Preferable hand</th>
<th>Number of flutings</th>
<th>$D_{\text{hand-WP}}$ (cm)</th>
<th>$WP_x$</th>
<th>$WP_y$</th>
<th>$WP_z$</th>
<th>$\psi_{az}$</th>
<th>$\psi_{el}$</th>
<th>$\psi_{ro}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB</td>
<td>Right</td>
<td>19</td>
<td>31</td>
<td>25.4 ± 1.1</td>
<td>−9.0 ± 1.7</td>
<td>16.0 ± 2.0</td>
<td>−20 ± 4</td>
<td>−27 ± 4</td>
<td>−107 ± 8</td>
</tr>
<tr>
<td>HM</td>
<td>Left</td>
<td>18</td>
<td>33</td>
<td>21.6 ± 0.9</td>
<td>10.5 ± 0.7</td>
<td>23.2 ± 0.3</td>
<td>38 ± 2</td>
<td>40 ± 4</td>
<td>−54 ± 4</td>
</tr>
<tr>
<td>HU</td>
<td>Left</td>
<td>20</td>
<td>28</td>
<td>21.4 ± 0.9</td>
<td>10.7 ± 0.4</td>
<td>14.8 ± 1.6</td>
<td>24 ± 1</td>
<td>−24 ± 4</td>
<td>88 ± 4</td>
</tr>
<tr>
<td>IN</td>
<td>Right</td>
<td>21</td>
<td>37</td>
<td>18.6 ± 0.7</td>
<td>−17.7 ± 1.4</td>
<td>26.6 ± 1.6</td>
<td>−46 ± 2</td>
<td>−43 ± 3</td>
<td>−86 ± 3</td>
</tr>
<tr>
<td>RA</td>
<td>Right</td>
<td>18</td>
<td>25</td>
<td>22.1 ± 0.8</td>
<td>−9.8 ± 1.0</td>
<td>6.9 ± 2.3</td>
<td>−31 ± 3</td>
<td>−7 ± 4</td>
<td>108 ± 4</td>
</tr>
<tr>
<td>YO</td>
<td>Right</td>
<td>22</td>
<td>28</td>
<td>21.2 ± 0.5</td>
<td>−12.4 ± 0.7</td>
<td>13.1 ± 1.3</td>
<td>−38 ± 2</td>
<td>−22 ± 3</td>
<td>106 ± 5</td>
</tr>
</tbody>
</table>
The direction of the stroke at time of contact was found by linear extrapolation of the direction of the WP velocity that has been calculated as a numerical derivative of WP coordinates. The stability of stroke direction was assessed by the maximal spread \( \Omega \) of the cone formed by the directions of different strokes (Figure 4).

**Calculating the Joint Angles and Their Coordination (Kinematic Synergies).** The method of calculating arm joint angles using STS recordings has been previously described (Biryukova et al., 2000; Prokopenko, Frolov, Biryukova, & Roby-Brami, 2001). The method is based on the model of the human arm consisting of rigid bodies connected by joints of invariant geometry. First, the geometry of the joints (i.e., the positions and orientations of the axes of rotation in the joints) are calculated individually for each craftsman from the data of the “passive rotations” series. Second, we calculated the time courses of rotation angles corresponding to the seven DoFs of the arm: abduction-adduction (Ab-Adw) and flexion-extension (F-Ew) in the wrist; pronation-supination (P-Se) and flexion-extension (F-Ee) in the elbow; and abduction-adduction (Ab-Ads), flexion-extension (F-Es), and rotation (Rots) in the shoulder.

We examined the linear covariation of the seven joint angles over time using a principal-component (PC) analysis. PCs were calculated separately for each trial of each participant. The covariation between joint angles was analyzed as follows: the vector of temporal variation of the seven joint angles \( \varphi_i(t) \) around their mean values \( \varphi_M(t) \) \((i = 1, 2, \ldots, 7)\) is represented in the PC analysis as a weighted sum of seven orthogonal compounds (a sum of PCs)

\[
\varphi_i(t) - \varphi_M(t) = \sum_k w_{ki} \xi_k(t)
\]  

(1)
where $w_{ki}$ is the weight of the variation of the joint angle $\theta_i$ in the $k$th PC. Each $k$th PC in Equation 1 is described by a vector (PC vector) of seven constant normalized signed weights $w_{ki}$ ($i = 1, \ldots, 7$), called PC loadings, and by a corresponding time-dependent scaling factor $\xi_k(t)$, called PC factor. The vector $w_{ki}$ defines the structure and the scalar factor $\xi_k(t)$ the metrics (temporal course and amplitude) of the multijoint stroke.

The covariation matrix (based on the nonnormalized angular values) was used for the PC analysis instead of the correlation matrix (based of the normalized angles). The latter increases the contribution of the angles with small excursions to the first principal component (PC1), whereas the former enhances the contribution of relatively large movements.

A large amount of total variance accounted for by PC1 indicates a high correlation between the variables and provides a low-dimensional description of the seven-dimensional joint space. The results of a preliminary analysis showed that joint angles are highly correlated during stroke performance, and the first two principal components (PC1 and PC2) account for 100% of total variance (Biryukova et al., 2005). This can be interpreted as an occurrence of kinematic synergies. In this case, the weights, $w_{ki}$, defining the contributions of joint angles in PC1 and PC2 adequately describe kinematic patterns. Joint-angles contributions in PC1 and PC2 are used below as the quantification of the multijoint arm movement during the execution of the stroke.

The correlation between the PC1 loadings was used for the assessment of the degree of mutual compensations of joint angles.

**Assessment of the Visco-Elastic Properties of the Arm.** A linear spring-like model is used in many studies as the first approximation of visco-elastic properties of the
neuromuscular system of the arm (Gomi & Kawato, 1997; Mah, 2001; Lacquaniti, Carrozo, & Borghese, 1993; Frolov, Prokopenko, Dufosse, & Ouezdou, 2006). In these models, elastic and viscous components of the arm-joint torques are assumed to be linearly depending on joint angles $\bar{\phi}$ and angular velocities $\bar{\omega}$. Assuming the joint torques to be proportional to the angular accelerations $\bar{\alpha}$, and the Jacobian of the arm $\partial \bar{r} / \partial \bar{\phi}$ to be constant during the movement, WP acceleration $\ddot{\bar{r}}$ will be linearly dependent on WP position $\bar{r}$ and on WP velocity $\dot{\bar{r}}$. As a consequence, this linear dependence will take place for the length of the WP trajectory:

$$\ddot{L}(t) = S(L(t - \tau) - L_{eq}) + V\dot{L}(t - \tau).$$

In this equation, $L$ is the length of the WP trajectory, $\dot{L}$ is the WP acceleration, $L$ is the WP velocity, $L_{eq}$ is the WP equilibrium position, $\tau = 50$ ms is the time delay related to the functioning of the stretch-reflex loop, $S$ is the apparent stiffness, and $V$ is the apparent viscosity.

Apparent stiffness and viscosity are the consequences of elastic properties of the arm joints. Joint equilibrium position, as well as joint stiffness and joint viscosity, may significantly change during the reaching movement (Lacquaniti et al., 1993; Gomi & Kawato, 1997; Mah, 2001; Frolov et al., 2006). However, the accuracy of the approximation of joint torques by linear spring-like model with constant angular equilibrium position, stiffness, and viscosity (equal to their mean values over the movement) was shown to be only about 10% larger than the accuracy of the approximation by the model with variable parameters (Frolov et al., 2006). WP trajectory resulting from the double integration of the equations of motion should be even less sensitive to the variation of these parameters. For this reason we assumed $S$, $V$, and $L_{eq}$ to be constant in our model.

$L = 0$ at the point of contact. The attraction of the WP to the point of contact is characterized by the negative values of $S$ and $V$. A linear regression algorithm is used to find $S$, $V$, and $L_{eq}$. The trajectories of all flutings were used to increase the number of data points for the linear approximation.

**Statistical Analysis**

Analysis of variance one-way ANOVA and the least significant difference (LSD) test with standard significance of $p < .05$ were used to find statistically significant differences in stroke directions, kinetic energy of the stroke, and the kinematic synergies for each participant. The results for which the statistical support is not given are considered as qualitative.

Multidimensional, nonparametric scaling techniques were used to assess the variability of kinematic patterns. The kinematic patterns are represented by the points in seven-dimensional (7-D) space of joint-angle contributions in PC1. In our case, the method of multidimensional, nonparametric scaling is the method of representation of mutual positions of the points in the 7-D space on the plane (in 2-D space). This method (a) provides the minimal distortion (in the sense of minimal sum of squares) of the distances between the points in 7-D space, and (b) reveals the structure of the initial set of points in the form of isolated groups or clusters (Kruskal, 1977).
Results

Execution of the Stroke

Initial Posture. Trunk position is defined by the coordinates and the Euler angles of Sensor 4, located on the acromion of the scapula (Figure 1). These values were extremely stable during movement execution in all participants; they varied by less than 0.5 cm for X, Y, Z coordinates and by less than 1° for Euler angles.

Initial arm positions, defined by the initial values of the seven joint angles, were statistically different for the six participants, $F(5, 100) = 104, p << .001$. For all participants, the initial positions varied by less than 7° (Table 2).

Kinematic Pattern of the Arm. The kinematic pattern of the arm is defined by the joint-angles excursions during the execution of the stroke. The joint angle is considered constant and equal to zero if its amplitude, averaged over all flutings, is less than 1°.

IN’s angular amplitudes were smaller than for all other participants for most of the DoFs (Table 3). The kinematic pattern was participant specific (see Figure 5 for two examples).

1. Wrist. Compared with the other DoFs, extension-flexion in the wrist had the largest excursion for all participants (Table 3). Depending on the trial, IN showed different excursions: (a) extension during the lifting phase and flexion during the downward phase of the hammer movement, (b) flexion during the lifting and extension during the downward movement, and (c) almost no flexion-extension. In contrast, RA (Figure 5) and the other participants showed a very regular flexion-extension in the wrist.

Abduction-adduction excursions presented smaller amplitudes and more interindividual differences than extension-flexion. IN, here again, showed different excursions depending on the trial—either abduction during lifting and then adduction during the downward movement or vice versa (Figure 5).

2. Elbow. Flexion-extension in the elbow had minor excursions compared with pronation-supination, used by all participants (Table 3). When the other participants performed supination-pronation sequences, HM performed pronation-supination.

3. Shoulder. All participants showed a larger excursion of abduction-adduction and rotation than of flexion-extension (Table 3).

Table 2 Initial Values of Arm-Joint Angles Averaging Over All Flutings: Means and SDs (in Degrees)

<table>
<thead>
<tr>
<th>Craftsman</th>
<th>Ab-Adw</th>
<th>F-Ew</th>
<th>P-Se</th>
<th>F-Ee</th>
<th>Ab-Ads</th>
<th>F-Es</th>
<th>Rots</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB</td>
<td>102 ± 3</td>
<td>−58 ± 2</td>
<td>−62 ± 2</td>
<td>−60 ± 6</td>
<td>−17 ± 4</td>
<td>33 ± 5</td>
<td>−58 ± 3</td>
</tr>
<tr>
<td>HM</td>
<td>102 ± 1</td>
<td>−53 ± 3</td>
<td>−103 ± 1</td>
<td>−112 ± 2</td>
<td>−23 ± 5</td>
<td>55 ± 1</td>
<td>−34 ± 4</td>
</tr>
<tr>
<td>HU</td>
<td>75 ± 2</td>
<td>−66 ± 4</td>
<td>−127 ± 7</td>
<td>−51 ± 6</td>
<td>−18 ± 5</td>
<td>35 ± 1</td>
<td>−44 ± 5</td>
</tr>
<tr>
<td>IN</td>
<td>111 ± 1</td>
<td>−86 ± 3</td>
<td>−82 ± 3</td>
<td>−75 ± 3</td>
<td>−6 ± 5</td>
<td>38 ± 2</td>
<td>−18 ± 6</td>
</tr>
<tr>
<td>RA</td>
<td>80 ± 2</td>
<td>−90 ± 3</td>
<td>−74 ± 4</td>
<td>−56 ± 2</td>
<td>−40 ± 4</td>
<td>47 ± 2</td>
<td>−43 ± 3</td>
</tr>
<tr>
<td>YO</td>
<td>84 ± 3</td>
<td>−74 ± 2</td>
<td>−79 ± 3</td>
<td>−61 ± 1</td>
<td>−22 ± 2</td>
<td>42 ± 1</td>
<td>−21 ± 2</td>
</tr>
</tbody>
</table>
Joint Coordination. Joint-angle coordination (defined by the amount of total variance accounted by PC1) varied from 79% to 98% depending on the participant. Compared with the others, IN’s joint angles were much less coordinated (PC1 = 79%), with joint-angle coordination being much more variable, whereas YO’s joint angles were the most coordinated (PC1 = 98%), with joint coordination being the least variable (Figure 6). There were no statistically significant differences between the joint-angle coordinations in AB, HM, and HU, $F(2, 54) = 2.8, p = .07$. IN’s coordination was statistically different from that of this group $F(3, 74) = 30.7, p << .001$, as well as RA’s coordination $F(3,71) = 6.1, p << .001$ and YO’s coordination $F(3, 75) = 33.2, p << .001$.

Joint-Angle Contributions. The relative joint contributions in both PC1 and PC2 (Figure 7) highlight the kinematic structure of the movement (Figure 5). Because the kinematic pattern of IN was dramatically different from other participants it will be analyzed separately.

First Principal Component (PC1). Wrist flexion provided the highest contribution to the movement. Its mean value varied from 0.8 to 0.98. The contributions of flexion-extension in the elbow and in the shoulder were smaller than other DoFs contributions. The contributions of other joint angles showed strong interindividual differences (Figure 7):

1. HM, HU, and YO used abduction-adduction in the wrist in addition to flexion-extension;
2. HM and HU used pronation-supination in the elbow; surprisingly, HM performed supination-pronation when the reverse rotation (pronation-supination) would have been in line with the direction of the stroke;
3. Elbow and shoulder angle contributions were much smaller than those of the wrist. AB showed higher contributions of abduction-adduction and rotation of the shoulder than other craftsmen.

The standard deviations of the angle contributions for those five participants were quite low, from .01 to .15 (Figure 7).

Second Principal Component (PC2). The contributions of joint angles in the PC2 were also interindividually different (Figure 7):
Figure 5 — Joint-angle time courses during all performed flutings for craftsmen IN and RA.
1. Abduction-adduction in the wrist provided the highest contribution in AB, RA, and YO;
2. Pronation-supination in the elbow provided the highest contribution in AB, HM, and YO;
3. Rotation of the shoulder had a large contribution in AB, HM, RA, and YO; RA and YO showed the largest contributions of abduction-adduction in the shoulder.

The standard deviations of the angle contributions in PC2 were larger than those in PC1 and varied from .05 to .67 (Figure 7).

The analysis of the time excursions of joint angles (e.g., as in Figure 5) showed that abduction-adduction in the wrist and abduction-adduction and rotation in the shoulder contributing in PC2 achieve their maximum earlier than flexion-extension in the wrist contributing in PC1. Consequently, the contribution in PC2 refers to the earliest stages of the movement and may be interpreted as a preparation of rapid wrist flexion in its final stage.

**Specificities of Joint-Angle Contributions in Participant IN.** As opposed to the kinematic pattern described earlier, all DoFs of the arm contributed in PC1 for craftsman IN. The contributions of pronation-supination in the elbow and of rotation in the shoulder were comparable to the contribution of the wrist joint. There was a large variation in these contributions from stroke to stroke; the standard deviation varied from .09 to .40 (Figure 7).
Figure 7 — Mean and standard deviations of joint-angle contributions in PC$_1$ and in PC$_2$. 
The contributions in PC₂ were even more variable; the standard deviation varied .16 to .52. There were no significant differences between the contributions in PC₂. It is worth noting that the same was true for craftsman HU (Figure 7).

To outline the previous results, a 2-D plot resulting from nonparametric, multidimensional scaling summarizing all the results of the interindividual differences of the kinematic patterns is shown in Figure 8. The distance between the points represents the distance between the kinematic patterns (the sum of square differences between joint-angles contributions) corresponding to different flutings. One can see that for the two principal components PC₁ and PC₂, IN had the most variable pattern. HM’s and HU’s patterns appear to be less variable than IN’s pattern, but more variable than AB’s, RA’s, and YO’s patterns. The patterns of AB, RA, and YO are enlarged on the bottom of Figure 8. YO’s joint-angle contribution in PC₁ is the least variable. The variability of joint-angle contributions in PC₂ is about the same for AB, RA, and YO.

**Mutual Angular Compensations.** Angular trajectories during stroke execution were found to be quite variable, especially in IN and HU (Figure 8). We suggest that this variation is not stochastic and that there is a mutual compensation of joint-angle contributions to keep a stable direction of final hammer velocity (Figure 4; Berkinblit, Gelfand, & Feldman, 1986; Cole & Abbs, 1986; Rosenbaum, Meulenbroek, & Vaughan, 2001; Yang, Scholz, & Latash, 2007). A negative statistically significant

![Figure 8](image)

**Figure 8** — Results of nonparametric, multidimensional scaling for joint-angle contributions in PC₁ and in PC₂. The distance between the points represents the distance between the kinematic patterns corresponding to different flutings. The lower part of the figure gives an enlarged view of the circled areas.
correlation between two angle contributions in PC, that produce the same direction of hammerhead trajectory was considered to be evidence of mutual compensation. Significant correlations for all possible pairs of joint-angle contributions for each of the participants are shown in Table 4.

The largest number of statistically significant correlations appeared in IN, the smallest in AB, RA, and YO, and intermediate in HM and HU. All participants except AB and RA presented a correlation between the DoFs in the wrist. There were no statistically significant correlations between the DoFs in the elbow and the DoFs in the shoulder, except for YO.

IN presented correlations between all arm joints: wrist–elbow, wrist–shoulder, and elbow–shoulder. AB and HM presented mutual compensation in nonadjacent joints, the wrist and the shoulder. HU and RA presented wrist–elbow and elbow–shoulder compensations (Table 4).

**Goal of the Stroke**

*Direction of the Stroke.* The mean dispersion in stroke directions $\Omega$ (see Figure 4) varied from 6° to 12° and the standard deviations from 3° to 6° depending on the participant. The largest and the most variable dispersion in stroke directions was found in IN: 12° ± 6°.

The direction of the stroke in a 3-D working space is mainly defined by lateral (following the axis X) and up–down (following the axis Z) directions (see Figure 1). These directions were strongly individual and statistically different: for the X direction, $F(5, 108) = 48.7, p << .001$; for the Z direction, $F(5, 108) = 43.6, p << .001$.

*Kinetic Energy of the Stroke.* The evaluated mean values of kinetic energy transmitted to the raw material varied from 0.06 to 0.18 J depending on the craftsman (Figure 9). There was no statistically significant difference among HM, HU, and IN, whose strokes were the most powerful, $F(2, 48) = .53, p = .59$. Similarly, there was no significant difference between RA and YO, whose strokes were the least powerful, $F(1, 35) = 1.4, p = .24$. AB was statistically different from HM, HU, and IN, $F(3, 66) = 7.6, p << .001$, as well as from RA and YO, $F(2, 53) = 8.0, p << .001$.

**Table 4 Statistically Significant Correlations Between Joint-Angle Contributions in PC**

<table>
<thead>
<tr>
<th>Craftsman</th>
<th>Wrist/Wrist</th>
<th>Wrist/Elbow</th>
<th>Wrist/Shoulder</th>
<th>Elbow/Shoulder</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F-Ew/Ab-Adw</td>
<td>F-Ew/P-Se</td>
<td>F-Ew/Ab-Ads</td>
<td>P-Se/Ab-Ads</td>
</tr>
<tr>
<td>AB</td>
<td>—</td>
<td>—</td>
<td>—-.78</td>
<td>—</td>
</tr>
<tr>
<td>HM</td>
<td>-.90</td>
<td>-.77</td>
<td>-.58</td>
<td>—</td>
</tr>
<tr>
<td>HU</td>
<td>-.59</td>
<td>-.47</td>
<td>—</td>
<td>-.39</td>
</tr>
<tr>
<td>IN</td>
<td>-.79</td>
<td>-.72</td>
<td>—-.39</td>
<td>—-.58</td>
</tr>
<tr>
<td>RA</td>
<td>—</td>
<td>-.42</td>
<td>—</td>
<td>—-.53</td>
</tr>
<tr>
<td>YO</td>
<td>-.69</td>
<td>—</td>
<td>—</td>
<td>—-.41</td>
</tr>
</tbody>
</table>
Control of the Stroke

Visco-Elastic Properties of the WP Trajectory. The approximation of the visco-elastic properties of the WP trajectory by a linear spring is reasonable; linear regression coefficients varied from .82 to .96 (Table 5), being the lowest in RA and YO. There was a large variability of the stiffness values between craftsmen: RA and YO demonstrated the lowest values, HM and HU the highest ones. The values of viscosity were positive in RA and YO, implying that these craftsmen do not use the viscous properties of their joints to decelerate the movement of the hammer. As for the equilibrium position of the hammer, it was beyond the point of contact for all craftsmen except for RA. In AB, the equilibrium position was the closest to the point of contact.

Discussion

The aim of the study presented here was to better understand the relationship between the three dimensions of any goal-directed action, as Bernstein (1991/1996, p. 274/234) put it: “what is the purpose of the action, what must then be done, and how must it be done.” In many experimental studies on goal-directed action, the purpose of the action is indistinguishable from the what to do. Stone knapping, as it is practiced by craftsmen in Kambhat, appears to be a good example for analyzing the relationship between these three dimensions of goal-directed action.
Table 5  Parameters of the Approximation of Working Point Trajectory by Linear Visco-Elastic Spring

<table>
<thead>
<tr>
<th>Craftsman</th>
<th>$S$ (1/s²)</th>
<th>$V$ (1/s)</th>
<th>$L_{eq}$ (cm)</th>
<th>$R_{cor}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB</td>
<td>–204</td>
<td>–1.0</td>
<td>0.4</td>
<td>.96</td>
</tr>
<tr>
<td>HM</td>
<td>–384</td>
<td>–2.2</td>
<td>–3.8</td>
<td>.96</td>
</tr>
<tr>
<td>HU</td>
<td>–467</td>
<td>–1.0</td>
<td>–1.9</td>
<td>.96</td>
</tr>
<tr>
<td>IN</td>
<td>–166</td>
<td>–1.5</td>
<td>–2.7</td>
<td>.90</td>
</tr>
<tr>
<td>RA</td>
<td>–127</td>
<td>6.8</td>
<td>4.3</td>
<td>.85</td>
</tr>
<tr>
<td>YO</td>
<td>–124</td>
<td>2.2</td>
<td>–1.1</td>
<td>.82</td>
</tr>
</tbody>
</table>

Note. $S$ is the apparent stiffness; $V$ is the apparent viscosity, $L_{eq}$ is the apparent equilibrium position; $R_{cor}$ is the coefficient of the linear regression.

What?

The what refers here to the functional properties of the task. As discussed earlier, one of the determinants of the flake characteristics is the force produced at time of contact, which depends on acceleration and mass of the hammer. However, we used the velocity vector and kinetic energy, computed from the hammer displacement, because it minimizes the error resulting from computation. To detach the desired flake (Figure 2c), an appropriate vector of the velocity of the hammerhead at the time of contact must be achieved. The direction of this vector in 3-D space (direction of the stroke) characterizes the relative orientation of the anvil, the stone, and the hammer, and its absolute value defines the amount of kinetic energy transmitted to the stone.

The cone of stroke directions was $6^\circ$ to $12^\circ$ depending on the craftsman. Considering the length of the arm segments and the handle of the hammer, this appears to be a rather small range of values. One reason for this might be that during the task, the hammering arm provides very stable movements of the hammer, whereas the postural arm, that is the arm holding the bead, provides the appropriate relative orientation of the bead relative to the anvil. Interestingly, between sequences of strokes, the craftsmen often strike the end of the anvil, which might serve as a kind of reference point for the highly regular movements of the hammerhead. This hypothesis can only be confirmed by reconstructing the relative orientations of the anvil and of the bead, which could be carried out from video recordings. In the frame of this hypothesis, both the hammering and the postural arm are simultaneously involved in a bimanual coordination activity.

Surprisingly, the largest cone of stroke direction ($12^\circ$) was found in the most expert craftsman, IN, contradicting the idea that expertise reduces variability of the working point trajectory (Bernstein, 1947). This result may be interpreted in terms of a more adequate adaptation to the position of the bead, which depends on the postural hand. This could explain why IN has the reputation of being able to knap beads of any shape or size.

Flexibility of postural control and its adaptability to different contexts was emphasized in many studies (see Massion, 1992, for review). Although the two
arms have quite different functions, they become, with increasing levels of motor skill, more and more functionally linked, thus reducing the number of parameters to be controlled. Similarly, it was speculated that highly trained pianists probably control fewer parameters than nonmusicians. This enables them to control bimanual movements much more efficiently with smaller neural networks (Jäncke, 2006).

The amount of kinetic energy transmitted to the stone was statistically the same for craftsmen HU, HM, and IN, who are recognized as the most qualified experts (Figure 9). The significant differences between these three craftsmen and AB can be explained by AB’s specific working experience (see Method). RA and YO were different from the others because of the smaller values of kinetic energy of their strokes. Apparently, these two craftsmen detach smaller flakes than others and adjust the final shape of the beads during other working operations (Bril et al., 2000). The vector of final velocity used for the characteristics of the produced functionality, therefore, reflects the quality of the production, which is not the same in all craftsmen, although they are all considered to be knapping experts.

This gives rise to the following questions: How are the functional characteristics of the task produced and how is the high stability of stroke directions achieved?

**How?**

The answer lies in the actual motor activity that leads to the movement of the hammer, which in turn produces the given velocity vector. The coordination of redundant DoFs necessary to achieve a functional goal has been widely discussed under the term of *motor equivalence*, which is the variable patterning of redundant DoFs for the completion of an invariant movement goal. Goal-equivalent joint combinations were studied for pointing, reaching, prehension, and pistol-shooting movements (Soechting & Flanders, 1989; Steenbergen, Marteniuk, & Kalbflieisch, 1995; Grea, Desmurget, & Prablanc, 2000; Scholz, Schöner, & Latash, 2000; Rosenbaum et al., 2001; Tseng, Scholz, & Schöner, 2002). Different kinds of perturbations of the moving arm were studied to assess the limits of kinematic variations in which task completion can still be guaranteed, such as unexpected change in orientation of the object to grasp (Desmurget et al., 1995), increasing the number of DoFs to control (Marteniuk, Ivens, & Bertram, 2000), as well as suppressing visual feedback (Ghez & Sainburg, 1995; Sergio & Skott, 1998; Tseng et al. 2002). Motor impairments were also considered to be a specific kind of perturbation that can alter movement kinematics (Latash & Anson, 1996; Cirstea & Levin, 2000; Roby-Brami, 2003; Roby-Brami, Hoffmann, Laffont, Combeaud, & Hanneton, 2005).

Constraints imposed in motor tasks by tool use can be considered to be a kind of perturbation resulting in a search for new motor solutions. Once more, Bernstein was the first to analyze the choice of redundant DoFs of the arm for labor movements; in his book from 1923 he gives a vivid description of hammering with a cold chisel.

Motor equivalence may occur more often the more difficult the task becomes (Marteniuk et al., 2000). Our analysis of kinematic patterns of stone knapping shows that among the multiple joint configurations, each craftsman builds up a favored one. Apparently, joint-configuration idiosyncrasy represents a fundamental feature of human kinematic patterns (see, for example, precision grip studies: Santello & Soechting, 1998; Grinyagin, Biryukova, & Maier, 2005), which might depend on
the individual, anatomical configurations as well as on the specific learning conditions. Here we would like to stress the importance of interindividual anatomical differences. The positions and orientations of the axes of rotation in the joints (see Methods section) varied considerably between craftsmen. For example, the angle between the abduction-adduction and the flexion-extension of the axes in the wrist varied from 85° to 114°, and the angle between the flexion-extension and pronation-supination of the axes in the elbow varied from 87° to 120° depending on the participant. The large interindividual differences in joint parameters can affect the joint contribution during the movement.

We had some a priori information about the differences in the levels of skill between the craftsmen. IN was considered to be at the highest level of expertise, whereas AB’s, HM’s, and HU’s levels were slightly lower. AB specialized mostly in one type of bead. RA’s and YO’s levels were considered to be the lowest within the group. The peculiarities of kinematic patterns are closely related to the differences in the level of skill.

IN’s kinematic pattern strongly differed from the others in two inherent features: (a) all DoFs in the wrist, the elbow, and the shoulder were involved in the movement and (b) there was a large interstroke variability (Figure 6). All other craftsmen used mainly flexion and adduction in the wrist, whereas AB used an additional abduction and rotation in the shoulder, HM and HU used an additional pronation in the elbow, and RA and YO used the wrist joint only. The kinematic patterns in all craftsmen were rather stable compared with IN’s pattern (Figure 6). However, for both PC1, which describes the final stage of the stroke, and PC2, which describes the preceding stages, we observed a decreasing variability from IN through HM and HU to AB, RA, and YO (Figure 8). On the basis of these results, we can conclude that the highest level of expertise is characterized by the use of a great number of DoFs and by flexible joint configurations.

A good similar example comes from the sport activity of tennis players. Beginners mainly use the shoulder, elbow, and wrist joint. As the stroke improves, the torso comes into play, specifically the rotation of the hip joint. Highly skilled tennis players use the entire kinematic chain of their body, including knee and ankle joints (Ivanova, 2005).

A variety of temporal joint configurations assuring the same functional goal represent a kind of flexible synergy. The notion of flexible synergy (Macpherson, 1991) is based on Bernstein’s definition of movement synergy as a high-level organizing principle in contrast to low-level muscular or joint synergies. These principles have been discussed from the point of view of adequate language in motor control (Berkinblit et al., 1986; Gelfand & Latash, 1998). Macpherson (1991) suggested that although joint synergies are not fixed, they are determined by simple rules of combination.

These rules can be manifested in interstroke variability of joint-angle contributions that was not stochastic: a mutual compensation took place (Tables 4). The largest number of joints compensating each other was found in HM, HU, and IN, the smallest in AB, RA, and YO. Craftsmen AB, IN, and HM showed mutual compensation even in the nonadjacent wrist and shoulder joints.

Mutual compensation would be expected because, as shown earlier, very different joint configurations all end up in a stable end effector (hammerhead) motion. Multijoint system control implies that different DoFs interact so that each of them
remains “its own master,” while simultaneously, the functional output is kept at a desired level and does not require intervention from the higher level of the hierarchy, even when one or more of the elements change their contribution (Berkinblit et al., 1986; Gelfand & Latash, 1998). In the frames of these principles, the capability to compensate the possible errors in joint motions seems to be a more important characteristic of the level of skill than the high coordination of motions in separate joints. The most expert IN showed the lowest coordination (Figure 6) but the highest mutual compensations (Table 4). In line with these results, it has been recently shown that there is an increase in the goal-equivalent kinematic variance during the adaptation to an unusual force field (Yang et al., 2007).

The principles of error compensation have been illustrated with the example of organization of reaching movements in humans (Rosenbaum et al., 2001), postural reactions in a two-joint motor task (Shapiro, Aruin, & Latash, 1995), force sharing among fingers (Li, Latash, & Zatsiorsky, 1998), speech movements (Abbs & Gracco, 1985), and precision grip movements (Cole & Abbs, 1986).

Our data suggest that the lesser experts are more rigid, whatever the parameter, be it the initial joint configuration, the choice of arm DoFs to complete the task, the interstroke variability, or the mutual joint-angle compensations.

We consider that the adjustment of the visco-elastic properties of the arm provides a possible mechanism of arm movement control (Feldman, 1979; Latash & Gottlieb, 1991; Biryukova et al., 1999). This adjustment is manifested in the spring-like properties of the WP trajectory (Mussa-Ivaldi, Hogan, & Bizzi, 1985; Frolov et al., 2006). In line with these findings, the WP trajectory in all craftsmen was successfully approximated (.82 < R < .96) by a linear visco-elastic spring with the equilibrium position close to the point of the stroke (Table 5). The hammer trajectories of RA and YO, the lesser experts within the group, were worse according to linear spring; the coefficients of the linear regression were smaller than in other craftsmen and the viscosity values were positive (Table 5). The individual choice of joint angles involved in the movement can be considered to be a specific tuning of the multidimensional spring, which approximates the seven visco-elastic springs in the arm joints.

**To What Purpose?**

We suggest that this question is crucial for a satisfactory interpretation of the results concerning the functional goal of the stroke and the arm synergies providing movement execution. The covariability among the multiple DoFs might indicate that individual angular trajectories are subordinate to the final shape of the bead, which can be considered to be an invariant parameter of the task. We believe that the cornerstone for motor planning may be found in multisensory experience associated with successful task performance (i.e., in our case, with the desired shape of the bead).

Several studies have identified so-called high-level parameters: the point of contact of index and thumb during pinching (Hepp-Reymond, Huesler, & Maier, 1996), lip closure during speech and the timing there (Abbs & Gracco, 1985), the trajectory of the hand in goal-directed reaching (Hogan & Flash, 1987), grip force in object grasping (Westling & Johansson, 1984), and ground reaction force in stance during posture control (Macpherson, 1988). In these tasks the end result can be immediately interpreted in terms of success or failure.
In contrast, the success (or failure) of the stone knapping task is the ultimate result of a long sequence of strokes. Among these strokes, the ones concerning the fluting (analyzed in this article) are the most important. The failure of any of the fluting strokes can lead to the failure of the task. The complexity of the bimanual coordination necessitates a long process of learning (up to 10 years for high-level experts), which guarantees the required relative orientation of the anvil, the stone, and the hammerhead, as well as correct hammer velocity at the time of impact. In the process of learning, the craftsmen build their own models of “needed future,” adapting an individually optimal way to complete the task.

One possible way is to stiffen the shoulder and the elbow and to perform the stroke primarily with the wrist only (as seen in craftsmen RA and YO, Figure 7). Another way is to relax the muscles in the elbow and shoulder and to use these joints not only to assure postural stability before the stroke but also to execute the stroke (as seen in the other craftsmen). Often craftsmen embrace their knee with the hammering arm. At first glance, this can be viewed as an additional constraint that helps fix the “postural” DoFs in the elbow and shoulder. Comparing the series in which craftsman HM places his arm on the knee with the series in which he leaves the arm free shows that the “postural” fixation of the DoFs concerns only the initial angular positions. Angular time courses were the same in both postures. Apparently, the knee support partly counteracts the weight of the arm and then helps to relax the elbow and the shoulder.

The number of joints involved in the movement and their combinations increase as a function of skill (the case of craftsman IN) resulting in an even greater dimensionality (a higher number of DoFs) of the arm. As a consequence, IN can easily adapt to different kinds of beads, as well as to possible internal and external perturbations. In contrast to the other craftsmen, IN amplifies most the movements of the hammer and much less so those of the joints (Table 3). This is because of the fact that IN holds the hammer far away from the head, thus obtaining the longest lever (Table 1). In such a way, he not only economizes the rotations in the joints, but also uses the elasticity of the handle to a greater extent than the others. Bernstein’s definition of dexterity (Bernstein, 1991/1996, p. 267/228) ideally describes the movements of IN, the best craftsman in Khambhat:

Dexterity is the ability to find a motor solution for any external situation, that is, to adequately solve any emerging motor problem correctly (i.e., adequately and accurately), quickly (with respect to both decision making and achieving a correct result), rationally (i.e., expediently and economically), and resourcefully (i.e., quick-wittedly and initiatively).

The characteristics of the different types of stroke execution discussed earlier could be observed because all recordings were made in the natural conditions of the workshop. Real-life tool use offers ideal situations to analyze functional movements that may take years of learning before reaching high levels of dexterity (Ericsson &
Lehman, 1996), a condition impossible to generate in laboratory studies. In contrast to laboratory studies, real-life tool-use movements are not constrained by special experimental conditions (e.g., artificially fixed DoFs, elimination of gravity, etc.) based on an a priori model of the movement. However, in the absence of special experimental constraints, unavoidable approximations need to be introduced; for example, the rigid body assumption used in our analysis was inaccurate for the link “hand + hammer” (Table 1), which affected the calculations of the vector of final velocity. However, after having assessed this inaccuracy, we felt that the means (i.e., the methodological limitations) justified the end (i.e., the insight gained from the use of a natural setting).

To conclude we would like to highlight two dimensions of our work:

1. Biomechanical parameters of movement execution—angular coordinations of the arm and the visco-elastic properties of the working point trajectory—are reliable indicators of the level of skill in stone knapping.

2. Although natural situations are often considered to be not sufficiently controlled, working with expert craftsmen contributes to a better understanding of how the constraints of the task and those of the human body interact during task completion.

Notes

1. The biomechanical analysis was undertaken in the frame of an interdisciplinary project associating archaeologists, psychologists, biomechanists, and neuroscientists.

2. For more details see Roux et al., 1995, and Bril et al., 2005.

Acknowledgments

The authors are grateful to Valentine Roux for organizing the experiment in Khambhat and for supporting our methodological approach to data analysis. We would like to thank Gilles Dietrich and Agnès Roby-Brami for their invaluable help for data acquisition recordings, M.A. Kulikov for statistical advice, and Eva David for her painstaking work in knapping time-keeping, A. Frolov and R. Bongers for helpful discussions, and an anonymous reviewer for fruitful comments.

This research was funded by the French Ministère délégué à la recherché et aux nouvelles technologies (ACI TTT P7802 n° 02 2 0440), by the Russian Foundation for basic Research (projects 07-04-01641a and 07-01-00642a), and by the European Union project FP6-2004-NEST-Path HANDTOMOUTH.

References


