Running heads: The first humans travelling on ice

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The first humans travelling on ice: an energy saving strategy?

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ABSTRACT.

Economy of locomotion is a constant challenge for animals, particularly when related to migrations and travelling. Our paper focuses on human locomotion and particularly on the development of ice skating. The aim of our research was to understand whether environmental features such as a strong presence of lakes (frozen in winter) could force humans to develop ice skates in order to limit the energy cost of travelling. We hypothesized that the energy saving principle was a determinant factor in the development of human locomotion on ice. Five healthy adult participants took part in the experiments, during which we recorded the speed (1.2 ± 0.3 m s^{-1}) and metabolic energy cost (4.6 ± 0.9 J kg^{-1} m^{-1}) associated with travelling on bone skates. Simulations were also performed in order to show whether the benefit given by the use of skates was different in the areas where ice skating seems to have evolved originally. The gain reachable by using bone skates could lead to an extremely high energy saving (equal to 10% of the energy needed to survive during the cold season) and differs significantly between the regions considered in this study. An analysis of the geometrical shape of lakes associated to fractal analysis of their distribution suggests that, in order to better adapt to the severe conditions imposed by the long lasting winters, Finnish populations could benefit more than others from developing this ingenious locomotion tool.

KEYWORDS: energetics, fractals, human locomotion.

INTRODUCTION

Naturally, life is supported by the balance between energy intake through food and energy used to stay alive. Two millennia ago, in order to survive, humans living in Northern countries needed also to go hunting and fishing during the long winters, when the conditions of the ground significantly raised the energy cost of travelling. The development of tools that enhance locomotion might have helped humans to limit this necessary energy expenditure and increased their survival chances. Through history, humans invented tools and strategies that helped make better use of the musculo-skeletal system and allowed for a more efficient travelling, particularly on land (di Prampero, 1986). The most recent example is the bicycle (Minetti, Pinkerton & Zamparo, 2001) and its variations, while the oldest is considered to be skis (Formenti, Ardigò & Minetti, 2005). The softness and depth of the snow covering the Scandinavian lands for several months every year determined a remarkable increase in the energetic demand of walking (Pandolf, Haisman & Goldman, 1976), which forced peoples inhabiting these harsh regions to develop new locomotion tools (Brown, 1959; Heathcote, Tebbutt & Maxwell, 1892; Munro, 1893). Similarly, as soon as a sufficient level of metallic technology was achieved and the condition of the roads improved, humans invented bicycles in order to travel faster while keeping the energetic economy of transport high. We hypothesized that, as happened with bicycles and skis, the energy saving principle might also have underlaid the development of ice skating. It seems clear that humans started skating on ice approximately in the second millennium BC, as proved by archaeological findings. However, no clear evidence supports any of the different hypotheses on where and why bone skating started. The most ancient archaeological specimens cannot be clearly ordered chronologically, thus clearcut information about where this form of locomotion started is currently unavailable (Brown, 1959; Goubitz, 2000; Heathcote et al., 1892; Luik, 2000; Muhonen, 2005; Munro, 1893; Roes, 1963). The oldest known ice skates were made of animal bones [mainly horse metatarsi (Jacobi, 1976)], most of which were found in areas where water covers more than 5% of the corresponding modern country, namely Finland (with over 60000 lakes), the Netherlands, Sweden and Norway. Many ancient bone skates were also found in the Northern part of Germany, where water represents only about 2% of the national area. Those five regions were considered in the present study. Apart from the Northern part of Norway, the territory of those five regions is mainly flat (CIA, 2007), so for our simulations we assumed that the land is level. Fewer and more recent findings come from Estonia, Poland, Belgium, England, Latvia, Moldova, Denmark and Hungary. Proportionally, Canada shows a strong presence of water, but no bone skates have been found to date in

North America. The aim of the present study was to understand whether the geomorphologic characteristics of a particular area in the world could force humans to develop a new tool, in order to reduce the metabolic cost of their journeys. During our experiments we measured the speed and energy cost of travelling on bone skates. Our results, together with values for walking on firm terrain or on snow taken from the literature, were used as input data for simulations of journeys between a number of locations. Through these simulations we calculated the energy cost and duration of travels in two conditions: “walking only” and “walking and skating” (Figure 1). For “walking and skating” simulations, we considered the straight path connecting two locations and used speed and energy cost values of walking and skating as appropriate. For the “walking only” condition lakes could not be crossed; in this situation, the shortest path on firm terrain was considered and the speed and energy cost of walking were used for calculations. In this paper, we bring evidence suggesting that the peculiar shape and distribution of the numerous lakes in Southern Finland possibly determined a stronger prerequisite than in any other areas for the development of this human powered means of transport. In this geographical region characterized by a harsh climate especially in winter, our ancestors had to face the dilemma of walking around several frozen lakes, an energetically demanding option, or crossing them, which could prove to be more convenient in terms of distance travelled, metabolic cost and/or speed. Applying a novel approach for the first time, we took into consideration a simple, but clear and significant scenario.

MATERIALS AND METHODS

Energetic measurements

We measured the metabolic energy cost of skating on bone skates by means of experiments performed in an indoor ice rink on a 130m path. Here, environmental parameters such as temperature, wind speed and direction did not change during the tests and would consequently not affect results recorded at different times of the day or in different days. We made replicas of bone skates resembling the original shape and material: horse metatarsi were pierced horizontally, perpendicularly to the main axis of the bone at the condyle level and at about 20 cm from it. Leather straps were passed through these holes and were used as bindings (inset

Figure 2). The undersides of the bones used for our experiments were 210 mm long and 14 mm broad dimensions similar to the values recorded on 23 bone skates measured at the British Museum (London, UK) and at the Fitzwilliam Museum (Cambridge, UK). Five healthy adult participants took part in the tests (mass 66 ± 5 kg, stature 172 ± 5 cm, age 22 ± 4 years); all of them had substantial previous skating experience. Oxygen uptake, carbon dioxide output and heart rate were measured breath-by-breath by means of a telemetric portable metabograph (K4b2, Cosmed, Italy). The energy cost of travelling ($J \cdot kg^{-1} \cdot m^{-1}$) was obtained from the ratio between steady-state net oxygen uptake ($J \cdot kg^{-1} \cdot s^{-1}$) and mean speed ($m \cdot s^{-1}$). Participants were informed about the aims, procedures and details of the study and signed an informed consent form to take part in the experiments. Ethics approval for the experiments was given by the Department of Exercise and Sport Science Ethics Committee (Manchester Metropolitan University). Before the beginning of each recording session, we measured the oxygen uptake at rest in the ice rink, in order to calculate later the net cost of skating. As described and shown in old books (Heathcote et al., 1892; Munro, 1893) and ancient paintings (Olaus Magnus, Historia 1555), this form of locomotion required a very peculiar movement pattern: propulsion came from the upper limbs pushing a stick on the ice between the legs while lower limbs, being kept almost straight, provided balance. In fact, bone skates did not have a blade that could provide grip and so the movement pattern was very different from that adopted by modern skaters. Participants were given one day to get used to travelling on bone skates and declared to feel comfortable after such training. During the recording session, we asked them to travel at a speed sustainable for approximately 8 hours, simulating quite a long journey. This speed was subjectively chosen by the participants on the basis of the perceived physical exertion needed to sustain the chosen speed; during the tests we recorded an average heart rate of 105 ± 4 beats per minute, indicating that the intensity of the exercise could presumably be sustained for about 8 hours. Four minutes of activity were allowed to achieve a steady state condition; oxygen uptake and speed of progression recorded from the fifth to the seventh minute were considered for further analysis.

Simulations

To estimate the amount of energy that could be saved by skating we calculated and compared the amount of energy and time needed to travel a distance of at least 480 km in each country, either by foot and skates, or by foot only. In 6 sub-areas of each country, we simulated a series of journeys connecting two points 10 km apart; journeys started from the centre of each sub-area and headed to 8 different angles (45 deg spaced). For the "walking and skating" simulations the distance to be travelled was constant (10 km), while for the "walking only" simulation, the distance to be travelled varied according to the presence of lakes to be avoided; if lakes were on the route, we measured the shortest path connecting the starting point to the final destination. Travel duration and total energy demand were calculated from the different cost and speed of skating and walking at the same metabolic power (5.3 W kg^{-1}). The associated skating speed was 1.2 m s^{-1} and the speeds of walking were 1.9 m s^{-1} and 0.9 m s^{-1} respectively on firm terrain and snow (see Figure 2).

Shape of lakes and water distribution

We measured, by means of satellite images (www.googleearthsite.com), the size and shape of 2737 lakes over a total area of 168,000 Km^2 (similar to the area of Florida). Supported by a good correlation between the calculated (according to major and minor axes) and measured perimeters of a subset of lakes (r^2 = 0.97, n = 340), calculations have been based upon the elliptical approximation of lakes shape. By doing this, the length of the calculated path was 0.93 times the length of the measured path, so it seems to be a good approximation of the actual one, even though the first is slightly underestimated. However, this equally occurred in all the five countries considered, leaving unchanged the relative differences between countries. Figure 3 shows the relationship between walking and skating performance and the eccentricity values (arithmetic mean) of the lakes measured.

As indices of complexity and homogeneity of water distribution, we calculated the fractal dimension (D_B) and lacunarity values (λ, summarizing the area fraction occupied by water and its geometry) for the areas in the five countries considered. The fractal dimension was calculated by means of box counting scans and calculations were performed on the average values for each sub-area. The lacunarity index was calculated by means of sliding-box-scans: 261 box size to image size ratios between 0.5% and 35% (each scanned at 24 different grid positions, nTOT = 6264 scans) have been taken into account for each sub-area. D_B quantifies the increase in detail with increasing magnification and is a measure of complexity. λ measures the deviation of a geometric object from translational invariance; it is a measure of how a geometric object fills space: if the geometric object is dense, lacunarity is small. (for details of box counting and sliding box scans methods: http://www.geocities.com/akarpe@sbcglobal.net/box.html#download).

RESULTS

Energetic measurements

Individual speed and energy cost results in response to skating are reported in Table 1. Metabolic results in Figure 2 show that skating on bones was twice as expensive as walking on firm terrain, but less expensive than walking on snow at the same speed (for the same aerobic power - hyperbolic curve - its high cost of transport involved low progression speeds).

Simulations

Paired-sample t-tests (significance set at $P < .05$) showed that in terms of energy demand (Figure 4) the advantage of using skates was significant in Finland (-59%), Sweden (-20%), Norway (-13%) and Germany (-1%).

A one-way ANOVA was used to compare the advantage of skating over the 240 paths considered in the five countries (Figure 4). When travelling between two given points, the calculated gain determined by the use of skates was different both in terms of time ($P < .001$, $F\ (4\ , 235) = 8.061$) and energy needed ($P < .001$, $F\ (4\ , 235) = 8.068$). Homogeneous subsets calculated with Tukey HSD post hoc test (significance set at $P < .05$) showed that using skates in Finland was significantly cheaper in terms of energy demand and allowed for quicker journeys than in any other areas. An extreme example of these simulations is shown in Figure 1.

Shape of lakes and water distribution

Because of the different energetic demand and time needed to travel across or around different lakes, knowing the values of their eccentricity is a critical step needed to support the hypothesis that skating on ice might have been particularly convenient in one specific area between those mentioned above. Assuming that the starting point and the destination lay at the extremities of the minor axis of a lake, we calculated that as long as the eccentricity of the ellipsis is greater than 0.48 (0 = circle), skating across required a shorter time than walking around the lake (Figure 3). In other words, for the same metabolic power, skating on bones was time saving if the walking path on firm terrain was 2.9 times longer than the skating path. For the average dimensions of the lake, in terms of energetic cost, skating was more economical than walking in all the countries considered, the walking distance being on average almost 8 times greater than the distance to be travelled on skates. Games-Howell post hoc test showed that the ratio between these distances is significantly greater in Finland than in all the other countries (+24%, $P < .05$).

The results reported above refer to the average lake in the different countries and need to be associated to the actual distribution of water and land in each country (Figure 4). In a region, for a given ratio between the area occupied by water and land, the shape of coastlines of individual lakes and complexity or regularity of their distribution influences the number and length of paths available between two points. In this perspective, despite the fact that routes chosen for the simulations did not follow the coastline, the calculation of fractal dimension values was important because the irregularity shown by the shape of the lakes proved to be a strong determinant of the length of the paths to be travelled. The results reporting fractal dimension and lacunarity values indicate the level of complexity characterizing the water/land distribution pattern and the homogeneity of this distribution for each country. These results are in agreement with the estimated energy costs of travelling, supporting the hypothesis that the necessity to develop new locomotion tools such as the bone skates could be stronger in areas in which water is complexly and homogeneously distributed.

DISCUSSION

Our study applies a new integrative method trying to understand if, in certain areas of the world, geographical and climatic features forced and induced man to develop a new tool such as the bone skate assisting human powered locomotion. In order to do this, we needed to know a relatively reliable figure of bone skating energy cost and speed and so measured oxygen uptake performing our experiments indoors, on an ice rink.

We showed how much energy could be saved by travelling in the two conditions taking into account: walking only versus walking and skating. The average daily energy requirement for an adult human is about 10.5 MJ (2500 kcal) (WHO, 2003) and this value rises to 1260.0 MJ for a period of four months, which roughly corresponds to the duration of the north European winters a few millennia ago (Brown, 1959). Our results make it possible to estimate that ancient Finnish hunters and fishermen, if walking and skating over 480 km could have saved 113 MJ, almost 10% of the energy needed to survive for four months. The net energy saved in Norway would be about 3%, while in the other countries it was less than 1%.

It is important to keep in mind here that geographical features changed through history, particularly in the Netherlands, where a network of canals started to be built in the 15th century. Ancient maps of the Netherlands show that a very large area was covered with water in the North of the country. Nevertheless, this would have probably discouraged people from crossing it on skates.

In winter hunters mainly used traps and fishermen had to travel on ice in order to find a crack where fish would swim near the surface and would be easy to catch (Hines, 2006). The lack of detailed maps and knowledge about adopted routes limit the extent to which we can understand how the presence of rivers affected the conditions of travelling. Nevertheless, we think that the limited width of a river could not justify the development of bone skates; bridges could be built instead.

Considering all the above reported evidence, our study could support the hypothesis that in the second millennium before Christ ancient Finns were more likely forced than populations living elsewhere to develop a tool which helped them save energy when travelling. In a time and environment in which the equilibrium between energy extracted from food and energy needed to live might be crucial, the minimization of the cost of locomotion might have helped humans to survive the severe conditions imposed by nature.

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Fig. 1 Two different lines connecting points A and B show the paths available for the walking only (red) and walking and skating (yellow) conditions.

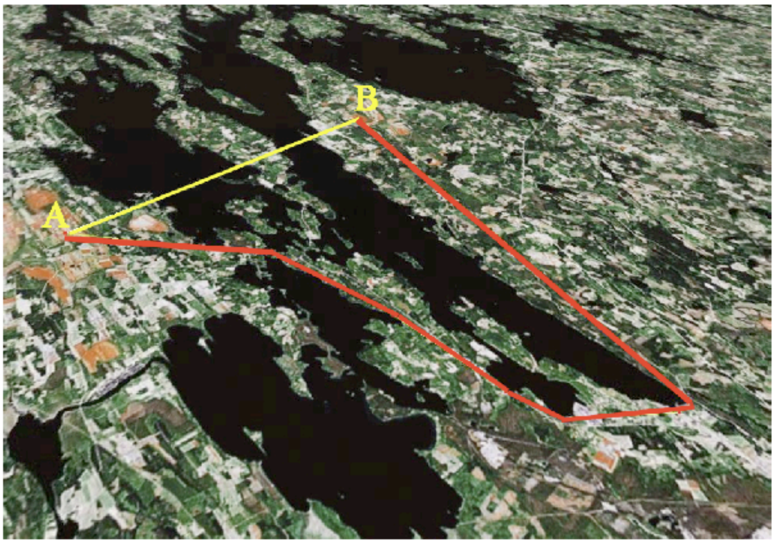


Fig. 2. The metabolic cost of skating on bones registered in our experiments is reported here as a function of speed. Data about walking and running on firm terrain (Margaria, 1976), modern ice skating (de Koning, Houdijk, de Groot & Bobbert, 2000) as well as the cost of historical skiing (Formenti et al., 2005) and walking on snow (Pandolf et al., 1976) (vertical dotted lines), which for a given speed depends on the depth of the footprint, are shown as means of comparison. In Pandolf's experiments, the speeds of walking were imposed and the depth of the foot-penetration (0, 10 and 20 cm) was measured in the footprints left in the snow by participants. Grey dots show values reported in literature for walking on snow with snowshoes (Connolly, 2002; Dalleck, DeVoe & Kravitz, 2003; Knapik, Hickey, Ortega & de Pontbriand, 2002). The light grey areas show the boundaries for the cost of walking and running in snow shoes (results from modern competitions), an indication of the limits imposed to locomotion in these circumstances. The iso-power curves indicate an estimated approximation of the performance sustainable for a given effort. The inset shows a bone skate used for the experiments.

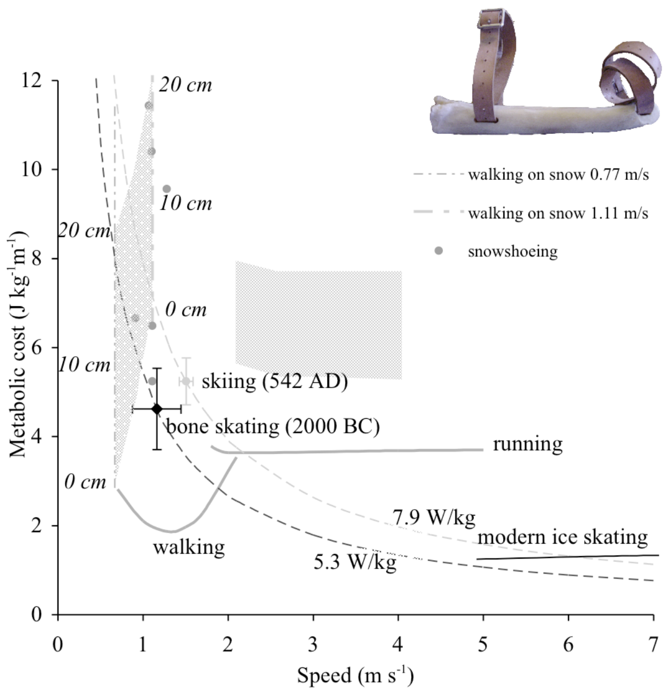


Fig. 3. The ratio between the cost (left) and the time (right) needed to walk (on firm terrain) and skate between two points is reported as a function of the eccentricity of the lakes. Only lakes with minor axis equal or greater than 1km were taken into account. Horizontal lines represent a ratio of 1 for cost (grey) and time (black). Values corresponding to eccentricity zero refer to a circular shape. A one-way ANOVA proved that the eccentricity of the lakes present in these countries is significantly different ($P < .001$; F (4 , 2732) = 39.23); similarly, also the ratio between the distance to be travelled across a lake and around it is different ($P < .001$; F (4 , 2732) = 34.94). The intersections between the lines indicating cost and time ratios and the vertical dotted lines show the gain given by skating in the different countries. In brackets the number of lakes observed in each area.

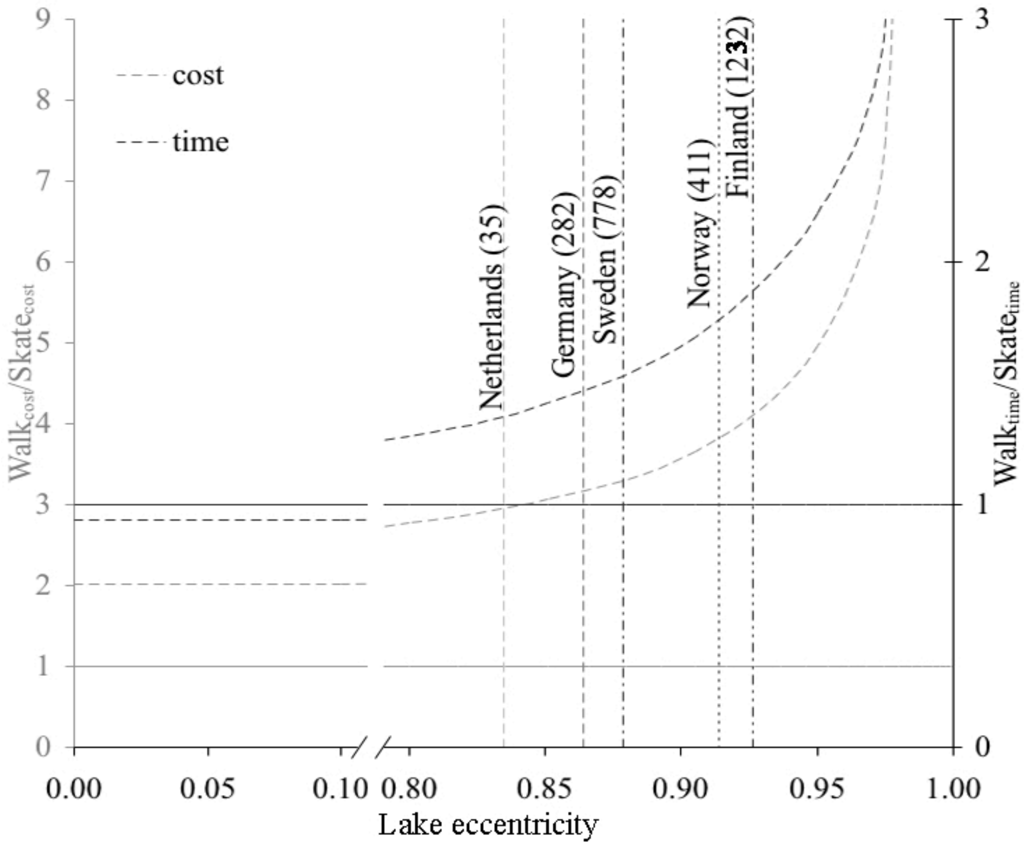
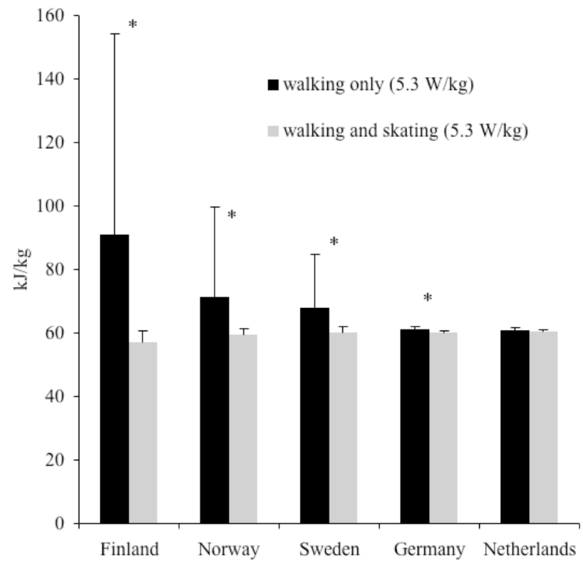


Fig. 4. The average and standard deviation values of energy cost associated to travelling between two points 10km apart is shown. Asterisks denote significant difference between the value relative to the walking only and the skating and walking conditions. For this graph, walking data refer to walking on snow, with footprints 5cm deep; if the comparison was made with walking on firm terrain, the gain would halve. Fractal dimension (DB), lacunarity (λ) values and land (km^2) to water (km^2) ratio (mean ± s.d.) are reported for each country. A one-way ANOVA proved that fractal dimensions ($P < .001$; $F\ (4\ ,\ 25) = 12.88$) and lacunarity values ($P < .001$; $F\ (4\ ,\ 7825) = 128.69$) were significantly different between the countries considered. Despite the statistical test for results about Germany being significant, the difference seems very small and it may be claimed that the test does not quite account for some underlying uncertainties. Tukey HSD post hoc test showed that Scandinavian countries represent a separated subgroup from Germany and the Netherlands.



	Finland	Norway	Sweden	Germany	Netherlands
D_B	1.71±0.05	1.47±0.07	1.47±0.03	1.13±0.34	1.01±0.25
λ	0.75±0.26	1.94±0.66	2.35±0.79	6.43±3.24	4.71±2.62
Land/Water	9.96%	5.05%	8.67%	2.18%	9.54%

Table 1. Speed and energy cost of skating on bones (subject-by-subject, average and standard deviation values).

Participant (n)	**Speed ($m\ s^{-1}$)**	**Cost ($J\ kg^{-1}\ m^{-1}$)**
1	1.3	4.8
2	1.5	4.3
3	1.2	3.5
4	1.2	4.4
5	0.7	6.0
Average±st.dev.	1.2±0.3	4.6±0.9