# Age-related change in duration of afterhyperpolarization of human motoneurones

M. Piotrkiewicz[1], L. Kudina[2], J. Mierzejewska[1], M. Jakubiec[1] and I. Hausmanowa-Petrusewicz[3]

[1]*Institute of Biocybernetics and Biomedical Engineering, Polish Academy of Sciences, Warsaw, Poland*
[2]*Institute for Information Transmission Problems (Kharkevich Institute), Russian Academy of Sciences, Moscow, Russia*
[3]*Neuromuscular Unit, Medical Research Center, Polish Academy of Sciences, Warsaw, Poland*

**Motor unit (MU) potentials were recorded from brachial biceps of healthy subjects aged 5.5–79 years. The subjects were subdivided into young (5.5–19 year) and adult (37.5–79 year) groups, between which single MU discharge characteristics were compared. Firing rates were in the ranges of 8.3–21.7 $s^{-1}$ (mean 12.87 $s^{-1}$) and 5.9–18.7 $s^{-1}$ (mean 11.08 $s^{-1}$) for young and adult groups, respectively. Standard deviations (S.D.) of interspike intervals (ISIs) were in the range 4.84–11.57 ms (mean 8.39 ms) for the young group and 4.26–12.23 ms (mean 7.76 ms) for the adult group. Both differences were statistically significant ($P < 0.001$). Special attention was paid to the previously developed method of ISI variability analysis, which enabled the comparison of MUs with respect to afterhyperpolarization (AHP) duration of their motoneurones (MNs). The results show that AHP duration increases gradually with increasing age, which is in line with the transformation of muscle properties towards a slower phenotype. This transformation seems to be a continuous process, covering the entire lifespan of a human being, from childhood to senescence. The results presented here are significant for their insight into the ageing process of the neuromuscular system. The age-related change in AHP duration has not been investigated previously in human studies and has been met with ambiguous results in animal studies.**

(Received 2 August 2007; accepted after revision 9 October 2007; first published online 11 October 2007)
**Corresponding author** M. Piotrkiewicz: Institute of Biocybernetics and Biomedical Engineering, Polish Academy of Sciences, 4, Trojdena Str., Warsaw, Poland. Email: masia@ibib.waw.pl

It is commonly known that force generation deteriorates with age. Extensive studies in a wide range of species, including humans (reviewed in Roos *et al.* 1997), have shown that muscle weakness is, at least partially, related to motor unit (MU) loss (Booth *et al.* 1994; Galea, 1996). The decrease in voluntary muscle strength is accompanied by slowing of muscle contraction, although the underlying physiological mechanisms remain unclear. Although preferential atrophy of fast muscle fibres is sometimes indicated as the main reason for conversion of muscle type from fast to slow (Deschenes, 2004), there is also substantial evidence against this view (Arabadjis *et al.* 1990; Galea, 1996).

Muscle force output is controlled by motoneurones (MNs), which are also affected by ageing. In animal studies, several changes in MN properties were observed which are in line with muscle contraction slowing: the decrease in axonal conduction velocity (Chase *et al.* 1985; Kanda & Hashizume, 1989) paralleled by slowing axonal transport of cytoskeletal elements (McQuarrie *et al.* 1989) and increase in MN input resistance (Chase *et al.* 1985; Morales *et al.* 1987). The common finding is the degeneration of MNs (Ansved *et al.* 1991; Caccia *et al.* 1979; Kanda & Hashizume, 1989) and their axons (Caccia *et al.* 1979). An increase in soma diameter, found in animal muscles (Liu *et al.* 1996; Miyata *et al.* 1993), may reflect the adjustment of aged MNs to the requirements of reinnervation; however, reinnervation appears to be impaired in ageing muscles (Gordon *et al.* 2004; Kawabuchi *et al.* 1998).

Information from human MNs is limited, but some studies have been published. In an autopsy study, Rafalowska *et al.* (1976) reported MN loss and morphological changes in axons, which might be responsible for slowing down their conduction velocity. Electrophysiological studies revealed a decrease in firing rates (e.g. Erim *et al.* 1999; Kamen, 2005; Barry *et al.* 2007) and a shift in recruitment thresholds towards lower force levels (Erim *et al.* 1999). All these findings are in line with the age change of human muscle fibres towards slower phenotypes. Studies comparing ISI variability between young and elderly subjects have yielded conflicting results; Laidlaw *et al.* (2000) reported an increase in variability in the elderly, whereas Barry *et al.* (2007) and Vaillancourt *et al.* (2003) did not find any difference.


DOI: 10.1113/jphysiol.2007.142356

Afterhyperpolarization (AHP) is an important property of a MN which is involved in control of MU firing rate. The AHP duration of a MN is known to be closely matched to the duration of twitch of its muscle unit (Kernell *et al.* 1999). Therefore, growing interest among human researchers in age-related changes in AHP (see, e.g. Christie & Kamen, 2006) is not surprising. The results from cat MNs are controversial; Morales *et al.* (1987) did not find any difference in AHP duration between young and aged animals, whereas Cameron *et al.* (1991) observed AHP elongation with age.

Our group developed a method for comparing single human MNs with respect to the duration of their AHP. The method is based on the analysis of the variability of interspike intervals (ISIs) of single MUs (Piotrkiewicz *et al.* 2001). In the present study we applied this method in order to investigate age-related changes in AHP duration.

## Methods

The experimental material is based on data collected from 16 healthy subjects in three previously published studies: 1) Piotrkiewicz *et al.* 1999 (8 control subjects, aged 5.5–19); 2) Piotrkiewicz *et al.* 2001 (4 subjects, aged 51–58); 3) Pitrkiewicz *et al.* 2005 (4 control subjects aged 37.5–79 years). The subjects from the first series of experiments will be reported further as the young group and the others as the adult group. None of the subjects had any record of a neuromuscular disease. Some of the subjects were investigated more than once. The experiments were performed in agreement with the declaration of Helenski. Each subject (or his/her parents) gave informed consent to the experimental procedures. For the last study, the procedures were approved by the ethical Committee of the Medical Research Center, Polish Academy of Sciences (earlier, no appropriate Ethical Committee existed).

### Experiments

During experiments, the subject was comfortably seated in an armchair. The potentials of single MUs were picked up by bipolar autoclavable needle electrodes (DISA, Denmark) with leading-off surfaces of 0.015 $mm^2$ (majority of adult subjects) or by electrodes made from fine wire of 90 $\mu$m diameter and introduced to the muscle by a hypodermic needle (young subjects). The idea underlying the choice of fine wire electrodes was to assure the maximum comfort of paediatric subjects. After insertion, the needle was withdrawn, whereupon the hooked ends of the wire kept the electrode firmly inside of the muscle. The electrodes were disposable and virtually painless. Both types of electrodes were autoclaved before the experiment, which minimized the risk of infection.

The data were collected from the brachial biceps (BB). The potentials of single MUs voluntarily activated during weak and moderate voluntary muscle contractions were amplified by an electromyograph DISA, Denmark and stored on a magnetic tape for off-line analysis. The subject was provided with visual and auditory feedback of the MU discharges and was instructed to keep the MUs firing steadily for 50–100 s. Several EMG fragments at different levels of muscle contraction strength were recorded to obtain as wide a range of firing rates as possible.

The data were transferred to a PC by an A/D converter with a sampling rate of 15–30 kHz. Specialized software was developed for all stages of the data analysis. More details on the experimental procedure are given in (Piotrkiewicz *et al.* 1999, 2001).

### Data analysis

Usually, potentials of several MUs that were simultaneously active were recorded in each experiment (Fig. 1). MU recordings were decomposed into constituent single MU potential trains by an operator–computer

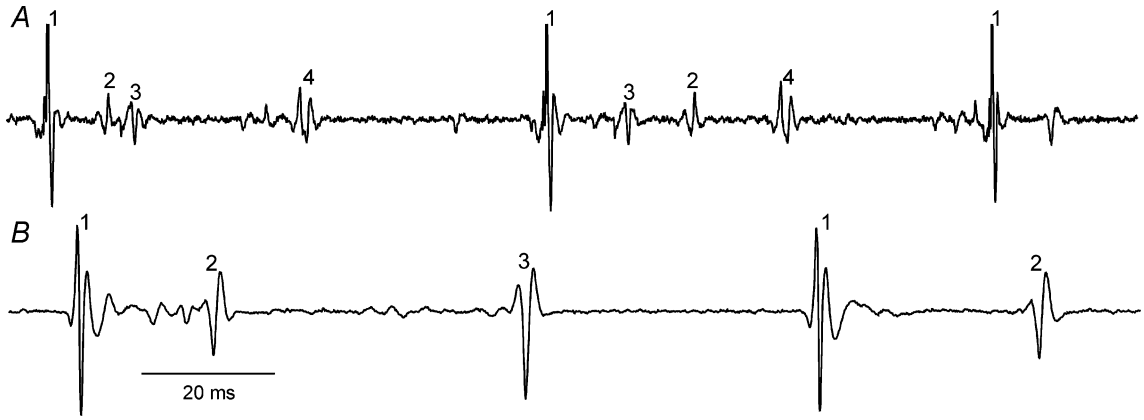



**Figure 1. Examples of EMG recordings from a young (*A*) and an adult subject (*B*)**
The potentials from the same MUs are marked with the same numerals

interactive method described in detail in Mazurkiewicz & Piotrkiewicz (2004). The results of the preliminary computer identification were verified by an experienced human operator who corrected the misclassifications. Only the sections of records with 100% proper identification were accepted for further analysis.

AHP duration was estimated from the dependency of the standard deviation of ISIs on their mean value (MISI), the s.d.–MISI relation. The typical relationship between these values is composed of two distinct short- and long-interval parts. This type of analysis was first introduced by the pioneer work of Tokizane & Shimazu

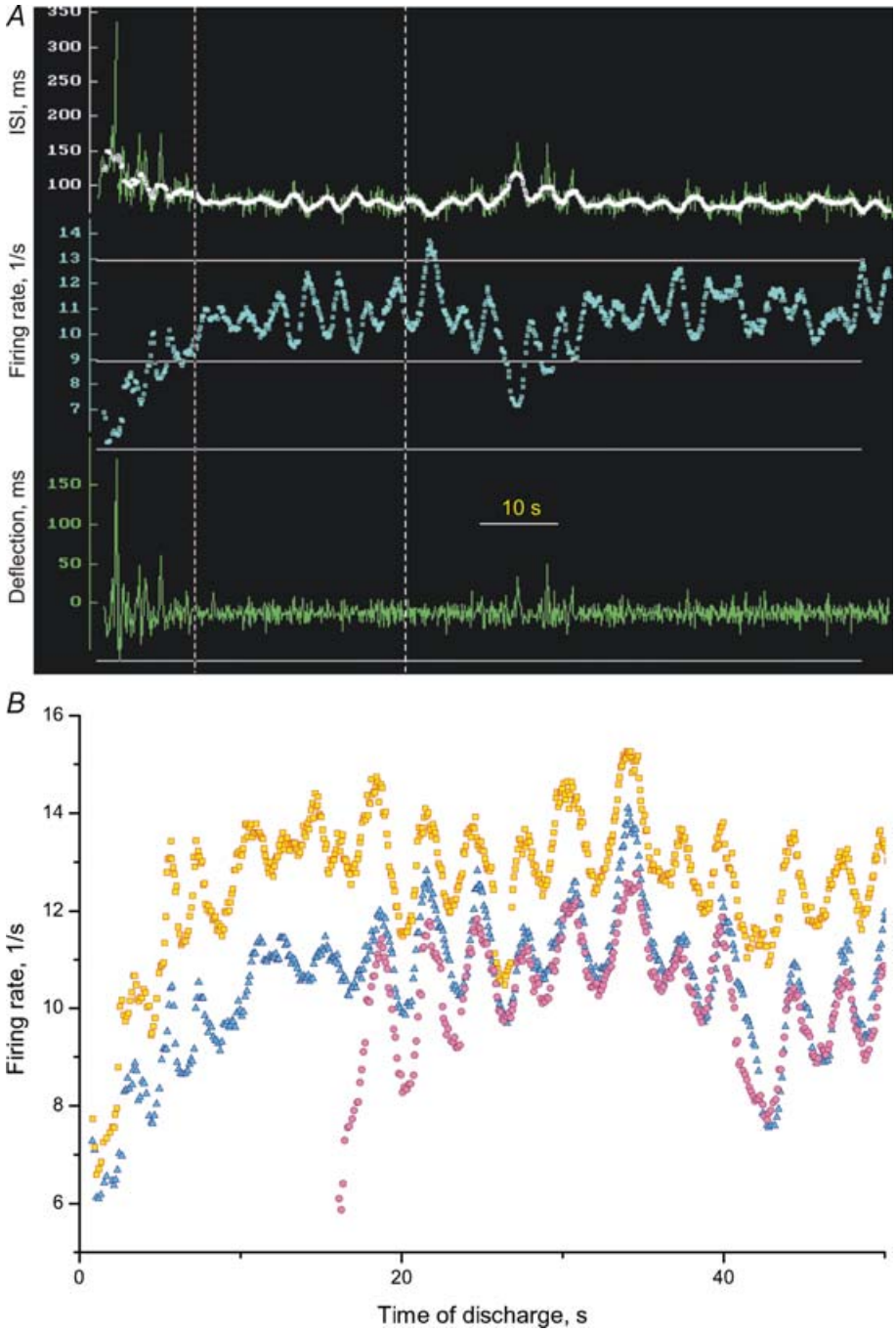
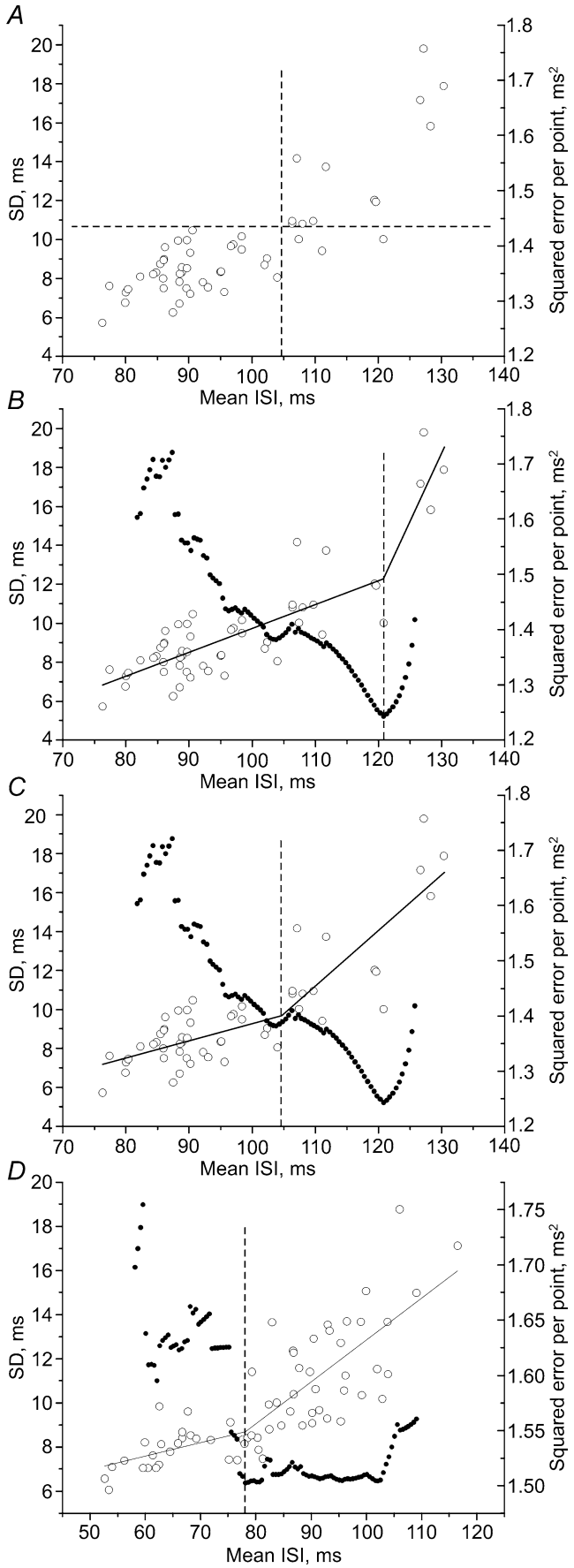



**Figure 2. Example of experimental single MU data**
*A*, computer screen presented to an operator. Abscissa: time of discharge; ordinate, upper panel, thin trace: interval from the previous discharge; thick trace: moving average calculated from 11 consecutive intervals; middle panel: instantaneous firing rate, calculated as a reciprocal of moving average; bottom panel: deflections from moving average. Vertical lines indicate beginning and end of a stationary fragment. *B*, instantaneous firing rates for 3 single MUs firing simultaneously, plotted *versus* time of discharge




(1964). Person (1993) proposed a hypothesis that the transition between short- and long-interval fragments of s.d.–MISI dependency is related to the AHP duration. Indeed, it has been shown by computer simulations (Piotrkiewicz, 1999) and in direct measurements from cat MNs (Powers & Binder, 2000) that the transition interval delimiting these two parts is correlated with the AHP duration for each single MN, although it is shorter than the AHP. This correlation was also confirmed in human experiments (Piotrkiewicz *et al.* 2001) where the transition interval was compared with AHP duration, which was estimated in specially designed experiments. The silent MNs were stimulated with double pulses; the interpulse interval was gradually increased and the time of excitability recovery after the first stimulus was taken as an estimate of AHP duration (method described in Kudina & Alexeeva, 1992).

Standard deviations and mean ISIs were calculated from the stationary fragments of MU potential trains, which were chosen by an operator according to the following procedure. The ISIs with their moving averages, computed over 11 consecutive values, instantaneous firing rates calculated as reciprocals of these averages, and deflections from the moving average were displayed on the computer screen as functions of time (an example is given in Fig. 2*A*). The operator indicated the fragments for which rate averages oscillated around a constant value and deviations from moving average were uniform (as between two vertical lines in Fig. 2*A*). Two horizontal lines, 4 Hz apart, were displayed to help the operator. In Fig. 2*A* slow fluctuations in mean firing rate can be seen. All MUs firing simultaneously fluctuated in parallel (Fig. 2*B*), which indicated that these fluctuations were caused by the common synaptic inflow to all MNs (common drive, De Luca *et al.* 1982). Thus, prior to the calculation of s.d., moving averages were subtracted from ISIs. The same method of calculation was applied in Tokizane & Shimazu (1964). The amplitude of slow fluctuations was lower in younger subjects. Each point was computed from not less than 60, and usually from 100 to 1500 ISIs.

For each subject s.d. was plotted *versus* mean value of ISI. In a typical pooled s.d.–MISI plot, short- and

**Figure 3. Illustration of the method of transition point estimation (large circles, s.d.; small circles, squared error sum normalized by the data number)**
*A*, raw data for the 58-year-old subject. Vertical line indicates the division point delimiting short- and long-interval ranges, set visually (note the difference in s.d. values between both fragments). *B*, the same subject, approximation lines fitted automatically with the division point corresponding to the minimum of squared error sum. *C*, the same subject, approximation lines fitted with the division point indicated by the operator. *D*, data for 7-year-old subject, approximation lines fitted automatically, the division point corresponding to the minimum of squared error sum is the same as that determined by visual inspection. The same data as those presented in Fig. 4.

long-interval ranges (with lower and higher S.D., respectively) could be determined by visual inspection (Fig. 3*A*). For each of these plots, the transition interval delimiting short- and long-interval sections was estimated as follows. The data were sorted accordingly to mean ISI and subdivided into two sets, with the initial division point set so that the short-interval section contained four data points. Straight lines were fitted to each data set by the least-squares method and the division point was systematically increased by 0.5 ms as long as the total least squares sum was obtained. Figure 3*B* shows a S.D.–MISI plot (large circles) with the squared error sum plotted against the division point (small circles). If there was a discrepancy between visual and automatic division (as in the example given in Fig. 3*B*), the division between the short- and long-interval ranges was indicated by the operator (Fig. 3*C*). There was always at least local minimum of the total squared error sum close to the division line. However, this discrepancy happened only in a few cases, and usually the minimum of the squared error sum corresponded well to the division determined visually (Fig. 3*D*). The transition interval was set at the intersection of the lines fitted by the least-squares method to the short- and long-interval ranges so determined. The procedure described above allowed estimation of a single value of mean AHP duration for all MNs analysed in each subject.

The statistical analysis of data was performed by the tools built into the program Statistica (StatSoft, ver. 6). The significance of differences was analysed by Student's paired *t* test and the regressions by Spearman's rank order correlations.

## Results

Altogether, 291 MUs were identified in the study, 189 from the young group and 102 from the adult group. MU firing rates were in the ranges 8.3–21.7 $s^{-1}$ (mean 12.87 $s^{-1}$) and 5.9–18.7 $s^{-1}$ (mean 11.08 $s^{-1}$), respectively. The difference was statistically significant ($P < 0.001$).

Typical S.D.–MISI dependencies are presented in Fig. 4 for a child (7 years, diamonds) and adult subject (58 years, asterisks). Both short- and long-interval fragments of the plot for the adult subject are shifted towards the longer MISI. Note that the ISI range of 79–102 ms (between vertical arrows indicating transition points) corresponds to the short-interval range for the older subject, and to the long-interval range for the younger subject. Therefore, over the range of 79–120 ms the variability is significantly higher for the younger subject ($P < 0.001$).

Figure 5 presents the relationship between transition intervals and the subject's age. The transition interval gradually increased with age. The regression line fitted to the pooled data was described by the equation $y = 0.441x + 78.083$ (correlation coefficient $r = 0.766$). This correlation was statistically significant ($P < 0.001$). When only adult subject's data were analysed, the correlation was much weaker (coefficient $r = 0.387$) and insignificant ($P > 0.22$), although the regression equation was virtually the same: $y = 0.455x + 77.265$.

ISI variability was compared between young and adult subjects in the short-interval range, meaning that for each subject only these S.D. values were selected, which corresponded to mean ISIs shorter than his/her transition interval. S.D. values were in the range 4.84–11.57 ms (mean 8.39 ms) for the young group and 4.26–12.23 ms (mean 7.76 ms) for the adult group. The difference was statistically significant ($P < 0.001$).

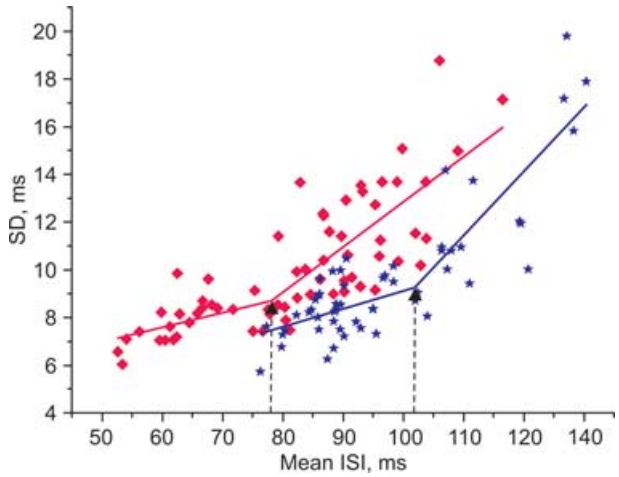



**Figure 4. Examples of S.D. H–MISI plot for 7- (diamonds) and 58- (asterisks) year-old subjects**
Transition intervals are indicated by arrows

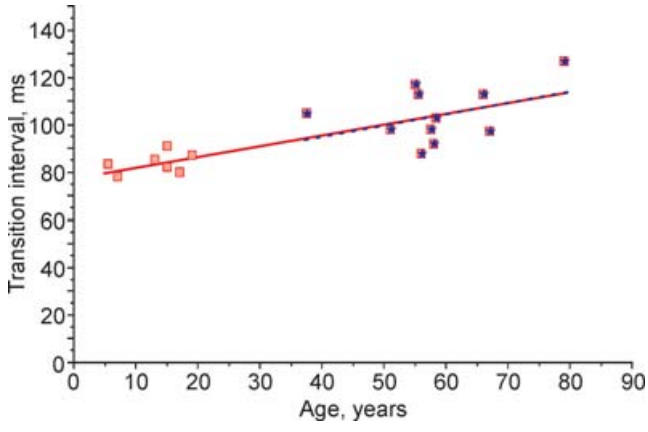



**Figure 5. Transition intervals, determined from pooled data, plotted *versus* age of a subject**
Squares, continuous line, pooled data; asterisks, dashed line, data for adult group. See text for regression equations

## Discussion

The method of estimation of transition interval applied in this study may give rise to certain controversies. The authors are aware of the fact, that when this method is applied to single MN data, it gives only a rough estimate of the MN 'fastness'. However, it has been shown by computer simulations (unpublished data) that different methods of transition interval estimation, including visual one, yielded always similar results, i.e. correlation between transition interval and AHP duration. The method applied here was chosen as comparatively simple, and objective in the majority of cases. The transition interval estimated from pooled data represents approximately the mean value of transition points for all different MNs analysed in a given experiment.

The s.d. strongly depends on the mean ISI, which had to be taken into account when comparing ISI variability between different age groups. It is clear from Fig. 4 that the result would depend on the ISI range over which the comparison is performed. This is a consequence of the difference in spike generating modes in short- and long-interval ranges. The short-interval range corresponds to the *rhythmic firing mode* (Calvin, 1974) when each consecutive spike is initiated as the result of the firing threshold crossing by the linearly rising membrane potential trajectory. In this mode, MN discharges are regular, their distribution is close to normal, and the ISI variability is low. The long-interval range corresponds to the *occasional spike mode* (Calvin, 1974) when a majority of ISIs is longer than AHP of the MN. In the final part of these ISIs the equilibrium membrane potential lies below threshold and the MN is being randomly excited by synaptic noise (Calvin, 1974; Matthews, 1999). In this firing mode, MN discharge is irregular, ISI distribution has an exponential tail of long intervals, and the variability increases rapidly with the mean ISI.

The most reasonable way to assess age-related changes in variability is to make the comparison at the same mode of spike generation. From the two modes described above, the one with rhythmic firing seems to be more appropriate, since the set of variability values here would be less dependent on the firing rate range, at which the data were collected. That is why in the present study the s.d. was compared between young and adult subjects in the short-interval range. This yielded an unexpected result; the variability was significantly higher for the young group, in contrast to the previous studies which reported either no difference (Vaillancourt *et al.* 2003; Barry *et al.* 2007) or higher variability in aged subjects (Laidlaw *et al.* 2000). These discrepancies are undoubtedly due to the differences in data collection and analysis. It should be stressed that the method of s.d. calculation, applied in this study, allowed for the estimation of the intrinsic variability of a MN. The slow fluctuations in the synaptic inflow, which were eliminated by this method, were more pronounced in older subjects and could have been responsible for the higher variability encountered by Laidlaw *et al.* (2000).

It has been shown previously that variability in the short-interval range was lower for MNs with shorter AHP (Piotrkiewicz *et al.* 1999; Powers & Binder, 2000). The computer simulations indicate that this is the case if AHP amplitude and synaptic noise level remain constant (Piotrkiewicz, 1999). The inverse relation between variability and AHP duration could be encountered, if longer AHPs had larger amplitude and a steeper ramp. Indeed, Zengel *et al.* (1985) has shown that the amplitude of 'slow' MNs' AHP is larger than that of 'fast' MNs. However, Cameron *et al.* (1991) reported that the increase in AHP duration in aged cat MNs was accompanied by a decrease in AHP amplitude. To a certain extent, this discrepancy may be due to the influence of anaesthetics (Button *et al.* 2006), which are commonly used in animal experiments and absent in human experiments. The age-related changes in membrane properties may also involve processes for which our simple model did not account. On the other hand, smaller variability in the short interval range could be related to decreased amplitude of synaptic noise. However, the single EPSP amplitudes in 'slower' MNs tend to be higher, and thus the inflow containing larger EPSPs can be expected to be more, not less, variable.

It should be noted that above 20–30% of maximum voluntary contraction force, it became increasingly difficult to distinguish single MU potentials so that we were not able to collect enough ISIs to perform variability analysis for higher-threshold MUs. Thus, our sample is limited to low-threshold MNs, presumably 'slow' ones. It has been shown (Zwaagstra & Kernell, 1980; Zengel *et al.* 1985) that among all MN types, the range of AHP durations in 'slow' MNs is the widest. One could thus expect also a wide scatter of transition intervals from randomly sampled MNs from different subjects. Moreover, the sample of MNs obtained from a given subject would depend on his/her preferred type and amount of physical activity and the differences in this respect could be expected to be much more pronounced in the adult group, compared to the young one.

The question about possible selective impairment of fast, high-threshold human MNs could not be solved because of the limitation of our MN sample. This issue calls for similar investigation, performed on MUs recruited on the highest levels of muscle contractions. The selective death of MNs supplying fast muscle fibres and subsequent reinnervation of denervated fibres by 'slow' MNs was indicated as a possible reason for MU remodelling (e.g. Kanda & Hashizume, 1989; Kadhiresan *et al.* 1996).

The correlation of AHP duration with age was statistically insignificant, when analysed in the adult group

separately. It was evidently due to the big scatter of experimental points and limited age range. This may also explain the discrepancy between the results of two studies investigating electrophysiological properties of cat MNs. Morales *et al.* (1987) compared AHP duration between young adult (1–3 years old) and old (14–15 years old) cats and found no statistically significant differences in their AHP durations. In contrast, Cameron *et al.* (1991) found an age-related increase in AHP duration in kittens *versus* cats.

The increase in the transition interval, found in the brachial biceps, means that there is a systematic increase in the AHP duration with age, which covers virtually the entire lifespan of a human subject. There were no dramatic changes in the elderly, such as were encountered for muscle force decrease (Vandervoort & McComas, 1986), which could suggest a pathological ageing process.

### Conclusion

The changes in S.D.–MISI dependency observed in this study indicate that there is gradual transformation of MN properties (in particular, AHP duration) with age towards a slower phenotype. This is in agreement with analogous findings concerning muscle contractile properties (Vandervoort & McComas, 1986; Skorjanc *et al.* 1998; Hook *et al.* 2001). The slowing of the neuromuscular system, in contrast to decreased muscle force, seems to be a continuous transformation, which begins in the childhood and continues until senescence. During this transformation, the good match of temporal characteristics of a MN and its muscle unit (Kernell *et al.* 1999) seems to be preserved.

## References


Ansved T, Wallner P & Larsson L (1991). Spatial distribution of motor unit fibres in fast- and slow-twitch rat muscles with special reference to age. *Acta Physiol Scand* **143**, 345–354.

Arabadjis PG, Heffner RR Jr & Pendergast DR (1990). Morphologic and functional alterations in aging rat muscle. *J Neuropathol Exp Neurol* **49**, 600–609.

Barry BK, Pascoe MA, Jesunathadas M & Enoka RM (2007). Rate coding is compressed but variability is unaltered for motor units in a hand muscle of old adults. *J Neurophysiol* **97**, 3206–3218.

Booth FW, Weeden SH & Tseng BS (1994). Effect of aging on human skeletal muscle and motor function. *Med Sci Sports Exerc* **26**, 556–560.

Button DC, Gardiner K, Marqueste T & Gardiner PF (2006). Frequency-current relationships of rat hindlimb $\alpha$-motoneurones. *J Physiol* **573**, 663–677.

Caccia MR, Harris JB & Johnson MA (1979). Morphology and physiology of skeletal muscle in aging rodents. *Muscle Nerve* **2**, 202–212.

Calvin WH (1974). Three modes of repetitive firing and the role of threshold time course between spikes. *Brain Res* **69**, 341–346.

Cameron WE, Jodkowski JS, Fang H & Guthrie RD (1991). Electrophysiological properties of developing phrenic motoneurons in the cat. *J Neurophysiol* **65**, 671–679.

Chase MH, Morales FR, Boxer PA & Fung SJ (1985). Aging of motoneurons and synaptic processes in the cat. *Exp Neurol* **90**, 471–478.

Christie A & Kamen G (2006). Doublet discharges in motoneurons of young and older adults. *J Neurophysiol* **95**, 2787–2795.

De Luca CJ, LeFever RS, McCue MP & Xenakis AP (1982). Control scheme governing concurrently active human motor units during voluntary contractions. *J Physiol* **329**, 129–142.

Deschenes MR (2004). Effects of aging on muscle fibre type and size. *Sports Med* **34**, 809–824.

Erim Z, Beg MF, Burke DT & de Luca CJ (1999). Effects of aging on motor-unit control properties. *J Neurophysiol* **82**, 2081–2091.

Galea V (1996). Changes in motor unit estimates with aging. *J Clin Neurophysiol* **13**, 253–260.

Gordon T, Hegedus J & Tam SL (2004). Adaptive and maladaptive motor axonal sprouting in aging and motoneuron disease. *Neurol Res* **26**, 174–185.

Hook P, Sriramoju V & Larsson L (2001). Effects of aging on actin sliding speed on myosin from single skeletal muscle cells of mice, rats, and humans. *Am J Physiol Cell Physiol* **280**, C782–C788.

Kadhiresan VA, Hassett CA & Faulkner JA (1996). Properties of single motor units in medial gastrocnemius muscles of adult and old rats. *J Physiol* **493**, 543–552.

Kamen G (2005). Aging, resistance training, and motor unit discharge behavior. *Can J Appl Physiol* **30**, 341–351.

Kanda K & Hashizume K (1989). Changes in properties of the medial gastrocnemius motor units in aging rats. *J Neurophysiol* **61**, 737–746.

Kawabuchi M, Chongjian Z, Islam AT, Hirata K & Nada O (1998). The effect of aging on the morphological nerve changes during muscle reinnervation after nerve crush. *Restor Neurol Neurosci* **13**, 117–127.

Kernell D, Bakels R & Copray JC (1999). Discharge properties of motoneurones: How are they matched to the properties and use of their muscle units? *J Physiol Paris* **93**, 87–96.

Kudina LP & Alexeeva NL (1992). After-potentials and control of repetitive firing in human motoneurones. *Electroencephalogr Clin Neurophysiol* **85**, 345–353.

Laidlaw DH, Bilodeau M & Enoka RM (2000). Steadiness is reduced and motor unit discharge is more variable in old adults. *Muscle Nerve* **23**, 600–612.

Liu RH, Bertolotto C, Engelhardt JK & Chase MH (1996). Age-related changes in soma size of neurons in the spinal cord motor column of the cat. *Neurosci Lett* **211**, 163–166.

Matthews PB (1999). Properties of human motoneurones and their synaptic noise deduced from motor unit recordings with the aid of computer modelling. *J Physiol Paris* **93**, 135–145.

Mazurkiewicz Ł & Piotrkiewicz M (2004). Computer system for identification and analysis of motor unit potential trains. *Biocybernetics Biomed Engineering* **24**, 15–23.

McQuarrie IG, Brady ST & Lasek RJ (1989). Retardation in the slow axonal transport of cytoskeletal elements during maturation and aging. *Neurobiol Aging* **10**, 359–365.

Miyata H, Sugiura T, Kawai Y & Shigenaga Y (1993). Effect of soft diet and aging on rat masseter muscle and its motoneuron. *Anat Rec* **237**, 415–420.

Morales FR, Boxer PA, Fung SJ & Chase MH (1987). Basic electrophysiological properties of spinal cord motoneurons during old age in the cat. *J Neurophysiol* **58**, 180–194.

Person RS (1993). Spinal mechanisms of muscle contraction control. In *Soviet Scientific Review*, ed. Turpaev TM, pp. 1–83. Harwood Academic Publishers, Newark, New Jersey.

Piotrkiewicz M (1999). An influence of afterhyperpolarization on the pattern of motoneuronal rhythmic activity. *J Physiol Paris* **93**, 125–133.

Piotrkiewicz M, Hausmanowa-Petrusewicz I & Mierzejewska J (1999). Are motoneurons involved in muscular dystrophy? *Clin Neurophysiol* **110**, 1111–1122.

Piotrkiewicz M, Hausmanowa-Petrusewicz I, Mierzejewska J & Jakubiec M (2005). Motoneuron 'fastness' in amyotrophic lateral sclerosis. In *Lecture Notes of 78th ICB Seminar 'Motoneurons and Motoneuron Pools'*, ed. Vrbova G, Piotrkiewicz M & Zmyslowski W, pp. 69–76. ICB, Warsaw.

Piotrkiewicz M, Kudina L, Hausmanowa-Petrusewicz I, Zhoukovskaya N & Mierzejewska J (2001). Discharge properties and afterhyperpolarization of human motoneurons. *Biocybernetics Biomed Engineering* **21**, 53–75.

Powers RK & Binder MD (2000). Relationship between the time course of the afterhyperpolarization and discharge variability in cat spinal motoneurones. *J Physiol* **528**, 131–150.

Rafalowska J, Drac H & Rosinska K (1976). Histological and electrophysiological changes of the lower motor neurone with aging. *Pol Med Sci Hist Bull* **15**, 271–280.

Roos MR, Rice CL & Vandervoort AA (1997). Age-related changes in motor unit function. *Muscle Nerve* **20**, 679–690.

Skorjanc D, Traub I & Pette D (1998). Identical responses of fast muscle to sustained activity by low-frequency stimulation in young and aging rats. *J Appl Physiol* **85**, 437–441.

Tokizane T & Shimazu H (1964). *Functional Differentiation of Human Skeletal Muscle*. Charles C. Thomas, Springfield.

Vaillancourt DE, Larsson L & Newell KM (2003). Effects of aging on force variability, single motor unit discharge patterns, and the structure of 10, 20, and 40 Hz EMG activity. *Neurobiol Aging* **24**, 25–35.

Vandervoort AA & McComas AJ (1986). Contractile changes in opposing muscles of the human ankle joint with aging. *J Appl Physiol* **61**, 361–367.

Zengel JE, Reid SA, Sypert GW & Munson JB (1985). Membrane electrical properties and prediction of motor-unit type of medial gastrocnemius motoneurons in the cat. *J Neurophysiol* **53**, 1323–1344.

Zwaagstra B & Kernell D (1980). The duration of after-hyperpolarization in hindlimb alpha motoneurones of different sizes in the cat. *Neurosci Lett* **19**, 303–307.

## Acknowledgements

This study was supported by the statutory grants from authors' institutes and partially by the grant no. 4T11E015125 from the Polish Committee of Scientific Research.