# Human Operator Neuromuscular Actuation System Model

**Article** · December 2016

DOI: 10.1016/j.ifacol.2016.12.044



**3 authors**, including:

M. Havlikova
Brno University of Technology


Zdenek Bradac
Brno University of Technology

Available online at www.sciencedirect.com
ScienceDirect
IFAC-PapersOnLine 49-25 (2016) 260–265

# Human Operator Neuromuscular Actuation System Model

L. Obšilová*. M. Havlíková**. Z. Bradáč***

*Department of Control and Instrumentation, Brno University of Technology (Tel: +420 541 146 449;
e-mail: xobsil01@stud.feec.vutbr.cz).
** Department of Control and Instrumentation, Brno University of Technology
(e-mail: havlika@feec.vutbr.cz)
*** Central European Institute of Technology, Brno University of Technology
(e-mail: zdenek.bradac@ceitec.vutbr.cz)

**Abstract:** Human operator occurs in the most control systems called Man-Machine Systems. The quality of control depends on characteristics of neuromuscular system model, which contains efferent and afferent muscle fibers. Efferent muscle ensures the limb moving. Afferent muscle transmits information about limb moving to the central nervous system. This paper describes physiology of efferent and afferent muscle. The muscle input signals are obtained from the visual stimulus, which are stochastic signals. In the area of linear dependence of variables can be used simplified description and create time invariant system. This paper deals with derivation of the physical model of efferent muscle fiber and afferent muscle spindle. This paper describes neuromuscular actuation system model, which is used to more precise description of MMS.



*Keywords:* Man-Machine System, human operator, neuromuscular system, efferent muscle fiber, afferent muscle fiber, model

## 1. INTRODUCTION

Human operator is a part of almost every control system. These systems are called Man-Machine Systems (MMS). The human operator holds the post of controller. The main advantage of human is a fast and flexible adaptation to new situation. Instead of machine human operator can not work without errors for a long time. The human behavior is influenced by current psychological state. [Pentlag, 1999], [Rasmussen, 1985]

The important part of the human operator is his neuromuscular system. The basic dynamics of the human operator and the quality of manual control depends on characteristics and abilities of the neuromuscular actuation system of the human operator [Havlíková, 2008]. It consists of motor neurons at the spinal cord level and their associated muscles, joints, peripheral receptors and sensors [McRuer, 1968].

The derivation of physical model of neuromuscular actuation system model is used to more precise description of MMS. The physical model consists of muscles, manipulators and sensors. The input signals of model are the results of the visual stimulus, which are stochastic signals. In the area of linear dependence of variables can be used simplified description and create time invariant system. The human operator performs response actions using neuromuscular system in closed feedback control loop. [Allen, 1970]

The feedback control loop is closed through human eyes. The feedback is always the part of control loop and represents the compensation component of control. In the Fig. 1 is shown the control loop of neuromuscular system, which is represented by the transfer function *G(p)*. The input signals of the model are different visual stimulus $u_1(t)$, $u_2(t)$, ... ,$u_n(t)$. The output signal of model is limb movement *x(t)* of the human operator. The error *e(t)* represents difference between the required input signal *u(t)* and the actual output signal *x(t)*.

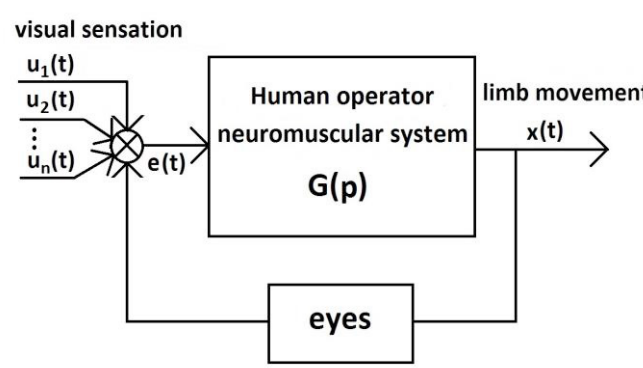


Fig. 1 Block diagram of neuromuscular system

Human operator neuromuscular system consists of two types of muscle fibers. These are efferent and afferent muscle fibers. Efferent muscle contains extrafusal fibers, which ensured limb moving according to motoric nerves commands. Efferent muscle fibers are inervated by the nerve impulses from the central nervous system using α-motoneurons axons. Afferent muscle contains muscle spindle, which consists of core of spindles and intrafusal muscle fiber. In the core of spindle is located the termination of nerve fiber axon, which is corresponded to a sensor. Intrafusal muscle fibers contain motoric path called γ-motoneuron, which transmit information about stimulus when change in length of surroundings extrafusal fibers to the central nervous system. [Trojan, 2003], [Vysoký, 2001]

2405-8963 © 2016, IFAC (International Federation of Automatic Control) Hosting by Elsevier Ltd. All rights reserved.
Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2016.12.044

## 2. EFFERENT MUSCLE PHYSIOLOGY

This chapter contains a description of efferent muscle physiology and equations which form the basis of efferent muscle physical model. Each muscle is characterized by its average tension $P_0$. Muscle tension is changed depending on the incoming motoneuron commands from the central nervous system [McRuer, 1968].

Relation between muscle length and its tension in response to motoneuron commands is expressed by tension-length and force-velocity curves. These curves were acquired by electromyographic measurement. Isometric tension-length curves are shown in Fig. 2, which shows several curves for different motor nerve firing frequency f. The muscle tension increased as the firing frequency increased at the same muscle length. Maximum and minimum firing frequency is shown in solid lines and is typical of skeletal muscles. [McRuer, 1968]

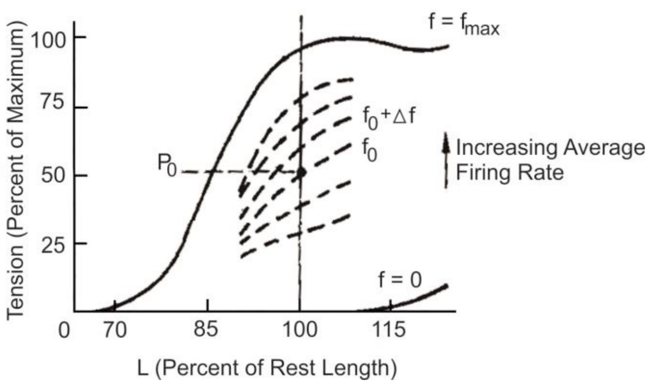


Fig. 2. Isometric tension-length curves [McRuer, 1986]

This functional dependence can be linearized when using only small changes of parameters around the operating point $P_0(L_0,f_0)$ [McRuer, 1986]. Then it is possible to linearize function using the first order terms in a Taylor series expansion.

$$P = P(L,f) \approx P_0(L_0,f_0) + \frac{\partial P}{\partial f}(f-f_0) + \frac{\partial P}{\partial L}(L-L_0) \qquad (1)$$

$$P = P_0 + C_f \Delta f - K_m \Delta L$$

where
- $P$ tension in the muscle
- $P_0$ tension at the operating point
- $\Delta f$ change in average firing frequency or average electrical activity
- $\Delta L$ change in muscle length
- $K_m$ slope of the tension-length curves for constant $f$
- $C_f$ slope of the tension-length curves for constant length

The values of $C_f$ and $K_m$ are evaluated at the operating point $P_0$.

Isometric curves force-velocity are shown in Fig. 3 for the several values of firing frequency *f*. Vertical axis shows muscle force *F* and horizontal axis represents velocity *V* of muscle shortening.

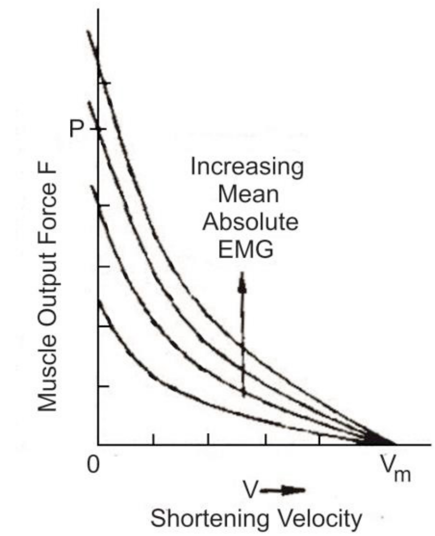


Fig. 3. Isometric force-velocity curves [McRuer, 1986]

The intersection between curves with vertical axis specify the size of the force $F_0$, which is equal to the muscle tension $P_0$. The force-velocity curves can be approximated by equation (2) [McRuer, 1986].

$$F = \frac{P(1-\frac{V}{V_m})}{1+\frac{V}{b}} \qquad (2)$$

where
- $V_m$ maximum velocity of shortening
- $b$ constant
- $P$ the isometric tension pertinent to the operating point length and muscle activity
- $F$ the muscle output force
- $V$ velocity of shortening

Around the operating point $P_0(L_0,f_0)$ for the small changes of parameters the function can be linearized using the first order terms in a Taylor series expansion [McRuer, 1986].

$$F = F(P,V) \approx F_0 + \frac{\partial F}{\partial P}(P-P_0) + \frac{\partial F}{\partial V}(V-V_0) \qquad (3)$$

The partial derivates are evaluated using the values of equilibrium state $V_0=0$, $F_0=P_0$ and equations (4) substituted into equation (3).

$$\frac{\partial F}{\partial P} = \frac{(1-V_0/V)}{(1+V_0/b)} \qquad (4)$$

$$\frac{\partial F}{\partial V} = -\frac{P_0(1/b + 1/V_m)}{(1 + V_0/b)^2}$$

$$F \approx P - P_0\left(\frac{1}{b} + \frac{1}{V_m}\right) \cdot (V - V_0) \quad (5)$$

$V_m$ maximum velocity of shortening
$V$ velocity of shortening
$b$ constant
$P$ the isometric tension pertinent to the operating point length and muscle activity
$F$ the muscle output force

Equation (1) is substituted into equation (3).

$$F = P_0 + C_f \Delta f - K_m \Delta L - B_m \Delta V \quad (6)$$

where
$F$ the muscle output force
$P_0$ tension at the operating point
$\Delta f$ change in average firing frequency or average electrical activity
$C_f$ slope of the tension-length curves for constant length
$\Delta L$ change in muscle length
$\Delta V$ change in velocity of shortening
$B_m = P_0(1/b+1/V_m)$, direct function of $P_0$
$K_m$ slope of the tension-length curves for constant $f$

## 3. EFFERENT MUSCLE PHYSICAL MODEL

The dynamics of muscle fiber can be described by physical model. This model applies only to condition of very small changes of values around the operating point $P_0$. Model consists of only one input signal and one output signal. The input signal is change in average firing rate $\Delta f(t)$ causing change in muscle strength. The output signal is change in manipulator position $\Delta x(t)$. The block diagram of efferent muscle with transfer function $G_E(p)$ is shown in Fig. 4.

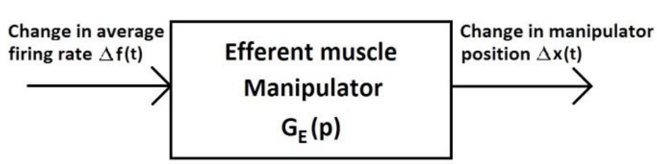


Fig. 4 Block diagram of efferent muscle

The physical model of efferent muscle is based on the above equations. The linearized equation (1) describes members of efferent muscle physical model. It consists of force source, spring and viscous damper. The size of force source is $P_0+C_f\Delta f$, change in force is causing by change in firing rate $\Delta f$. The force source is coupled to parallel combination of spring $K_m$ and viscous damper $B_m$. [McRuer, 1986] The next element of model is the muscle ensuring the movement called manipulator, which contains spring $K_c$ and damper $B_c$. The last part of model is weight $M$ of efferent muscle and manipulator. The dynamics of efferent muscle is shown in Fig. 5.

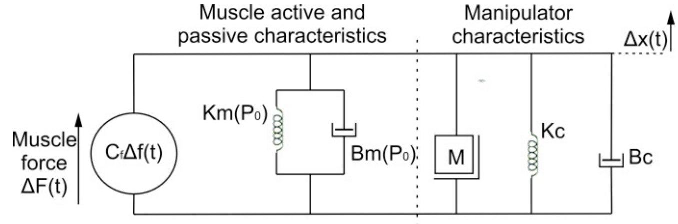


Fig. 5 Schematic of efferent muscle [McRuer, 1986]

The above model is described by differential equation in time domain (7) [Havlíková, 2008].

$$F(t) = C_f \Delta f(t) = (K_m + K_c) \cdot \Delta x(t) + (B_m + B_c) \cdot \frac{d\Delta x(t)}{dt} + M \cdot \frac{d^2 \Delta x(t)}{dt} \quad (7)$$

$F(t)$ muscle force
$\Delta x(t)$ time change in limb position
$C_f$ slope of the tension-length curves for constant length
$\Delta f(t)$ time change in average firing rate or average electrical activity
$B_m$, $B_c$ damping coefficient of muscle and manipulator
$K_m$, $K_c$ spring coefficient of muscle and manipulator
$M$ weight of efferent muscle and manipulator

Differential equation (7) is transformed using Laplace transform from the time domain to the frequency domain.

$$F(p) = C_f \Delta f(p) = (K_m + K_c) \cdot \Delta x(p) + (B_m + B_c) \cdot p \cdot \Delta x(p) + M \cdot p^2 \cdot \Delta x(p) \quad (8)$$

$F(p)$ Laplace transform of muscle force
$C_f$ slope of the tension-length curves for constant length
$\Delta f(p)$ Laplace transform of change in average firing rate or average electrical activity
$\Delta x(p)$ Laplace transform of change in muscle length
$B_m$, $B_c$ damping coefficient of muscle and manipulator
$K_m$, $K_c$ spring coefficient of muscle and manipulator
$M$ weight of efferent muscle and manipulator

Transfer function of efferent muscle $G_E(p)$ is derived from the equation (8).

$$G_E(p) = \frac{\Delta x(p)}{\Delta f(p)} = \frac{C_f}{(K_m + K_c) + (B_m + B_c) \cdot p + M \cdot p^2} = \frac{\frac{C_f}{M}}{p^2 + \mathrm{p} \cdot \left(\frac{B_m + B_c}{M}\right) + \left(\frac{K_m + K_c}{M}\right)} \quad (9)$$

## 3. AFFERENT MUSCLE SPINDLE PHYSICAL MODEL

Afferent muscle spindles transmit information about changes in tension or length in surrounding muscles to central nervous system. Afferent muscle spindle consists of intrafusal fiber, which is sensitive to static length transformation and dynamic compression deformation in surrounding extrafusal muscle fibers. When extrafusal muscle fibre changes its length $\Delta L$ the tension $P$ in intrafusal fiber is changes also. The result is change in motor nerve firing frequency $\Delta f$. [Havlíková, 2008]

A block diagram of afferent muscle spindle is shown in Fig. 6. The model contains two inputs. It is static and dynamic fiber of intrafusal fiber. The first input of physical model is change in firing frequency of static fibre $\Delta f_s(t)$, which depends on its extension $x_m(t)$. The second input of model is change in firing frequency of dynamic fibre $\Delta f_d(t)$. The output signal of model is effective muscle length $x(t)$.

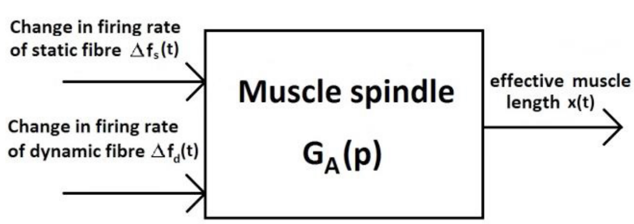


Fig. 6 Block diagram of muscle spindle

The physical model of intrafusal fibre of afferent muscle spindle is based on the same principle as the physical model of efferent muscle [McRuer, 1986]. Muscle spindle model is shown in Fig. 7.

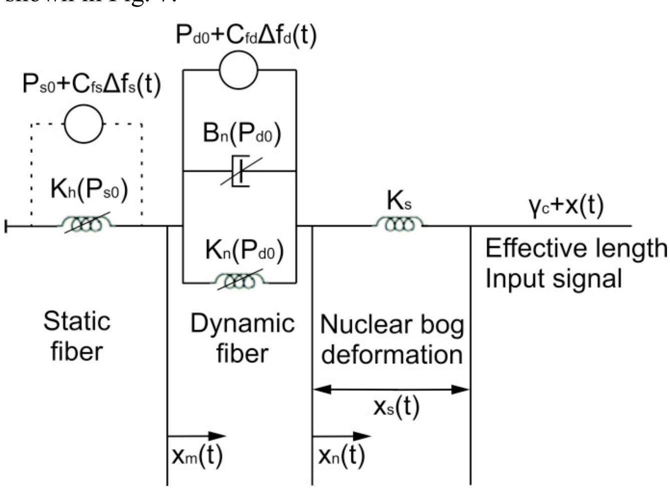


Fig. 7 Schematic of afferent muscle spindle [McRuer, 1986]

The static fibre contains only spring and force source $P_s(t)=P_{s0}+C_{fs}\Delta f_s$ (which is known as gamma command $\gamma_c$). Damper character is very weak at the static fibre. Therefore it can be neglected. The force source of the dynamic fibre is $P_d(t)=P_{d0}+C_{fd}\Delta f_d$. The last part of model is the nuclear bog deformation, which is characterized by spring $K_s$. The afferent muscle spindle movement is described by the equation (10). [McRuer, 1986]

$$\begin{bmatrix} K_s + K_n + B_n p & -(K_n + B_n p) \\ -(K_n + B_n p) & K_h + K_n + B_n p \end{bmatrix} \cdot \begin{bmatrix} x_n \\ x_m \end{bmatrix} = \begin{bmatrix} P_s - P_d \\ P_d \end{bmatrix} = \begin{bmatrix} K_s(\gamma_c + x) - P_d \\ P_d \end{bmatrix} \quad (10)$$

| | |
|---|---|
| $K_h$, $K_n$, $K_s$ | spring coefficient of static and dynamic fibre and nuclear bag deformation |
| $B_n$ | damping coefficient of dynamic fibre |
| $x_m$ | extension of static fibre |
| $x_n$ | extension of dynamic fibre |
| $\gamma_c$ | gama command causing extension of static fibre |
| $P_d$ | the force source of dynamic fibre |

The afferent muscle spindle output signal is described by the equation (11).

$$x_s(t) = \big(\gamma_c + x(t)\big) - x_n(t) \quad (11)$$

| | |
|---|---|
| $x_s(t)$ | nuclear bag deformation |
| $\gamma_c$ | gama command causing extension of static fibre |
| $x_n(t)$ | extension of dynamic fibre |
| $x(t)$ | effective length of displacement |

After adjusting of the equations (10), (11) it is obtained the muscle spindle transfer function $G_A(p)$ [Havlíková, 2008].

$$G_A(p) = \frac{\Delta x(p)}{\Delta f(p)} = \frac{K\left(p + \frac{1}{T_{A1}}\right) \cdot (\gamma_c + x) + \frac{P_d}{B_n}}{\left(p + \frac{1}{T_{A2}}\right)} = \frac{K_A(T_{A1}p + 1)}{(T_{A2}p + 1)} \quad (12)$$

$$\frac{1}{T_{A1}} = \frac{K_n}{B_n}$$

$$\frac{1}{T_{A2}} = \frac{K_r + K_s}{B_n}$$ parametres of time constants and gains

$$\frac{1}{K} = \frac{1}{K_h} + \frac{1}{K_s}$$

$$K_A = K \cdot T_{A1} \cdot T_{A2}$$

| | |
|---|---|
| $K_h$, $K_n$, $K_s$ | spring coefficient of static and dynamic fibre and nuclear bag deformation |
| $B_n$ | damping coefficient of dynamic fibre |
| $P_d$ | the force source of dynamic fibre |

*Δf(p)* Laplace transform of change in average firing rate or average electrical activity

*Δx(p)* Laplace transform of change in afferent muscle length

## 4. NEUROMUSCULAR ACTUATION SYSTEM MODEL

Neuromuscular system model consists of afferent and efferent muscle fibers. Each muscle contains muscle pair agonist / antagonist, which is used to movement. During moving one muscle generate stronger tension than second muscle, first muscle is shorten and second muscle is extended.

In the nearby area of each muscle is located intrafusal fiber [McRuer, 1974]. Commands of α-motoneurons $\alpha_c$ and $\alpha'_c$ comes from the spinal cord. These commands control extrafusal muscle fibers. The γ-motoneurons control movement of muscles according to commands $\gamma_c$. The $\gamma_c$ command control agonist muscle and $\gamma'_c$ control antagonist muscle. The block diagram of muscle pair Agonist/Antagonist is displayed in Fig. 8. The output signal of model is the response action *x(t)* caused by muscle pair agonist/antagonist. [McRuer, 1974], [Havlíková, 2008]

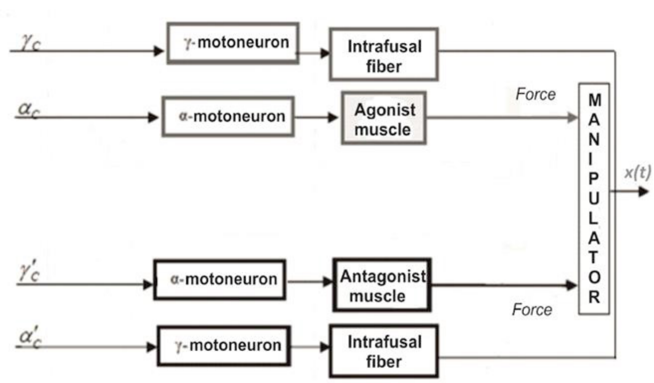


Fig. 8 Block diagram of muscle pair Agonist/Antagonist [McRuer, 1974]

The neuromuscular system model of human operator contains afferent muscle fiber with transfer function $G_A(p)$ and efferent muscle fiber with transfer function $G_E(p)$. The block diagram of neuromuscular actuation system is displayed in Fig. 9. The input signals are commands of α-motoneurons and γ-motoneurons, which arrives to muscle with transport delay $e^{-\tau_\gamma p}, e^{-\tau_\alpha p}$. This transport delay is created during transition commands from the central nervous system to the muscle fiber on long nerve fibers. The output signal of model is extension *x(t)* of efferent muscle manipulator, which depends on change in firing frequency $\Delta f_a(t)$ and the value of coefficient $C_f$. Change in firing rate $\Delta f_a(t)$ depends on position of manipulator *x*. This is the reason that in schema is the feedback which ensuring the information about manipulator position *x*. [Havlíková, 2008]

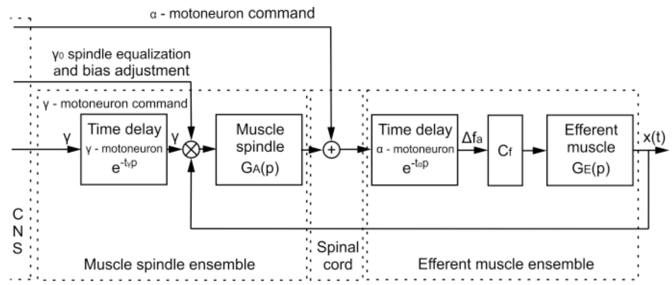


Fig. 9 Neuromuscular actuation system model [McRuer, 1986]

## 5. CONCLUSIONS

The paper describes the derivation of neuromuscular actuation system model which is used to more precise description of Man Machine Systems. At present the human operator has an irreplaceable role in MMS. It was derived the physical model and the transfer function of efferent muscle using linearization based on Taylor series. This model can be used only for small changes of parameters around the operating point. The model of afferent muscle spindle is based on the same principle as the physical model of efferent muscle. The difference is that the afferent muscle model contains two inputs. In the paper, the neuromuscular system model of human operator was described. This model consists of muscle pair Agonist/Antagonist which is used to limb movement.

The authors using neuromuscular system model for human behavior modelling in control loop of different structure and complexity. It is used for monitoring and evaluating of the driver´s fatigue and for the description of dynamic behavior of pilots.

## ACKNOWLEDGEMENTS

The completion of this paper was made possible by the grant No. FEKT-S-14-2429 - „The research of new control methods, measurement procedures and intelligent instruments in automation" financially supported by the Internal science fund of Brno University of Technology.

## REFERENCES

Allen, R. W. and McRuer, D. T. (1970) The man/machine control interface – pursuit control, *Automatica*, vol. 15, p. 681 – 686.

Havlíková, M. (2008). *Diagnostic of Systems with Human Operator*, Doctoral Thesis (in Czech), p. 33-47, Brno University of Technology, Brno.

McRuer, D.T., Krendel, E. S. (1974). *Mathematical Models of Human Pilot Behavior*, p. 22-25, AGARD-AG-188.

McRuer, D.T., Magdaleno, R. E., Moore, G. P. (1968). A Neuromuscular Actuation System Model, *IEEE Transactions on man-machine systems*, vol. 9 (3), p. 61-71.

Pentlag, A. et. al. (1999) Modeling and Prediction of Human Behavior, *Neutral Computation*, vol. 11, p. 229-242.

Rasmussen, J (1985). *Information Processing and Human-machine Interaction*. An Approach to Cognitive Engineering, New York: North-Holland.

Trojan, S., Langmeier, M. (2003). *Lékařská fyziologie*, p. 73-110, Grada Publishing, Praha.

Vysoký, P. (2001). Central fatigue identification of human operator, *Neutral network world*, vol. 11, p. 525-535.