SOME NEUROMUSCULAR ASPECTS OF HUMAN MOVEMENTS AND THE CONSEQUENCES FOR THE MUSCULAR REHABILITATION

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The findings and the knowledge resulting from the last two decades provide a basis for the organization of efficient and economical training practices that lead to progressive improvements in performance.

STRUCTURE OF STRENGTH AND MUSCLE ACTIONS

From a classical point of view strength can be divided in maximal strength, power and strength endurance. Maximal strength, power and strength endurance are not distinct entities and bear a hierarchical relationship to one another. **Maximal strength** is the basic quality which influences strength endurance and power. On the basis of factor analysis, concentric, isometric and eccentric maximal muscle actions are not independent from one another but this might be not correct with respect to the physiological adaptations caused by training regimen with different muscle actions. Nevertheless, an increase in maximal strength brings about an increase in power and therefore in movement speed, whereas the correlation between isometric maximal strength and movement speed increases when the load gets heavier The influence of maximal strength on strength endurance depends on the load and the time span of work, the higher the load and the shorter the working time the higher the correlation.

Power refers to the ability of the neuromuscular system to produce greatest possible impulse in a given time period. The time period depends on the resistance or the load against which the subject has to work and on the organisation of the acceleration. In other words, it is the capacitiy of the neuromuscular system to overcome resistance with the greatest contraction speed possible.

For the production of a great impulse an increase in force at the beginning of a muscular contraction is necessary as well as the ability to continue the developing of the already initiated force, i.e. the **rate of force development (RFD)**. Additionally for higher resistance the **maximal strength** influences the impulse production more and more. For movement in isometric or concentric manner with a duration up to 250 ms RFD is the main factor. Movements with a duration of more than 250 ms are dominated by the maximal strength factor.

Beside concentric and isometric actions powerful movements are generated in reactive movements or in a **stretch-shortening** cycle (SSC). A stretch-shortening cycle is not only a combination of an eccentric and a concentric movement. Moreover, this type of action is a relatively independent motor quality (Gollhofer 1987; Komi 1992). The quality of power production in a SSC is essentially dependent on the structure of the innervation pattern and the training state of the tendomuscular system in terms of their contractile and elastic abilities (Komi 1986; Schmidtbleicher et al. 1988). For power performance in a SSC the correlation between maximal strength and power output are fairly low.

Strength endurance refers to the ability of the neuromuscular system to produce the greatest possible sum of impulse in a definite time span by resisting "to fatigue" in long term strength performances. We know nowadays that the adequate time span for strength endurance performance is up to 2 minutes, otherwise the energy production would be more aerobic than anaerobic. In that case we would deal with endurance conditions rather than with strength endurance.The intensity of work must exceed 50% of maximum to guarantee better improvements in the anaerobic compared to aerobic capacity. To generate the greatest possible sum of impulse two conditions must be fulfilled: i. the single impulse should be as great as possible.This demand is depending from the factors already described above for the components of power (RFD and maximal strength); ii. the fatiguing influences has to be diminished: especially for short term work - less than 40 s - neuronal factors can limit performance in strength endurance. In long term work rather metabolic than neuronal processes reduce the capacity of strength endurance.

Comparable to power, also in strength endurance the movements generated in **a SSC** are independent from the strength endurance qualities produced in isometric or concentric muscle action (Frick 1993).The quality of strength endurance production in a SSC is dependent on the same factors mentioned above but additionally from the ability of central and peripheral nervous fatigue.The correlations between aerobic capacity and strength endurance in SSC are low.

We can conclude that maximal stength as a basic component plays an important role. Other meaningful components are the RFD and the fatigue resisting factor, especially of the nervous system. Metabolic influences are getting more and more important in aerobic conditions.

Beside concentric, isometric, eccentric and stretch-shortening cycled movements we should spend our attention also on other phenomena of neuromuscular behavior. Up to now only less results are reported about other **"combinations of basic motor actions"** compared to SCC. The combination of different types of muscle action provide possibly more effective and efficient type of training. One attempt was the philosophy of **isokinetic** training. Normally the relation in the angle-force curve depends on the joint position and the strength components of the afected muscles. In most training skills, movements start in an unfavourable condition with respect to the joint position. Therefore only small loads are used for exercises with the effect, that the stimulus characteristics are less effectiv than they could be. Isokinetic apparatus correct the angle-force relationship by systematically variation of the resistance, according to the enhanced force production that is reached with better biomechanical lever arms.The obviously better results with isokinetic training apparatus are **not due to a "specific isokinetic contraction"**. The better results are caused from the variations in the duration of the training stimulus. In isokinetic movements the duration of the training stimulus is prolonged, compared to traditional methods, and therefore the measurable effects are much better.

Another important question also related to muscle action, is the use of rotatoric or translatoric systems, i.e. open and closed chains. Both systems have advantages and disadvantages. **Rotatoric systems** are characterized by the following advantages: They allow the precisely stimulation of a specific muscle or muscle group, and this is due to diagnostics and training.The differences in laterality can be detected for single muscles or muscle groups. The disadvantages of rotatoric systems consist firstly in calibration because of the demand of similarity of joint axis and movement axis of the apparatus and this is secondly also true for the practice of training.Thirdly problems can occur, concerning disbalancies in synergistic, antagonistic and stabilizing muscles using rotatoric systems. The problems stem from the fact that only single muscles or one muscle group will be activated whereas other muscles from the chain are not stimulated.

Translatoric systems on the other hand are simply to calibrate because they have not the problem of similarity of joint and apparatus movement axis. In diagnostics as well as in training procedure disbalancies were avoided.The weakest muscle or muscle group of the chain is stimulated and therefore trained.Translatoric systems therefore posess high prognostic validity for movements in daily life and in sportspecific movements. The correlation coefficients between 20m sprint, long jump from standing conditions and medicine ball throw and the diagnostic results of translatoric measurements vary from r =.70 to r =.85. For rotatoric systems the correlation coeficients for the same variables are considerally lower, r =.30 to r =.35. The disadvantages of translatoric systems are the advantages of rotatoric systems. Measurements and diagnosis on translatoric systems are not valid for single muscles or a muscle group. No diagnosis is possible for the weakest muscle and therefore no selective adaptation of single muscles or muscle groups after training are detectable.

To conclude, the question is not to chose a rotatoric or a translatoric system, both systems have advantages and disadvantages and for diagnosis and training it would be useful to work with both systems because they are really distinct.

ADAPTATION EFFECTS

The described results are based on dynamography, kinemetry, electromyography, muscle biopsy techniques, computertomography, electrogoniometry and accelerometry as well as biomechanical methods and others. Science needs both, differentiation and integration and therefore interdisciplinary cooperation involving different fields - for example physics, sportmedicine, biochemistery, neurophysiology and others. One should handle these results as less or more significant or important measurements of specific devices and questions. In practice the human being has to decide, if the training procedures are for him or her adequate or not.

In training practice, it is believed that strength training merely calls for changes in enzymatic quantity or quality within the muscle, which ultimately results in muscle cross-sectional increases. Based on this perceived "fact", several types of sports discourage the use of strength training, since the apparently significant increase of body mass arising from muscle-cross sectional hyperthropy negates the desired positive effect of the improvement of power. In this context it has to be pointed out that an increase in maximal strength is always connected with an improvement of relative strength.

Apart from muscle hypertrophy there are other means of increasing maximal strength, power and strength endurance. The adaptation of the nervous system to the training stimulus plays an important role here. From the classical cross-innervation studies of Buller et al. (1960 a,b) and a large number of subsequent studies, we know that the fibre-specific typing of muscle depends on the consistency and utilization or nonutilization of those nerve cells in the spinal column that innervate the corresponding muscle fibres. It could also be shown that the nervous system reacts very sensitively in terms of adaptation to slow or fast contraction stimuli. Longitudinal studies on humans showed clear evidence that following a high intensity strength training session there exists an improvement in the ability to quickly mobilize greater innervation activities (Moritani, DeVries, 1979; Schmidtbleicher, Bührle 1987). Beside the ability of the motoneurone pool to tolerate higher activation**frequencies** or more rapid **recruitment** of motor units and an increased firing rate in contrast to the untrained state, another possibility of adaptation exists; i.e. a more **synchronized discharge** of the motoneurones so that activation bursts discharge a greater number of muscle fibres in a shorter time period. The results of this type of adaptation show a consider ably improvement of RFD (Schmidtbleicher 1980, Sale 1992).

Another possibility for the improvement of maximal strength and RFD results from improved **intramuscular coordination**. This means that the relation between excitatory and inhibitatory mechanisms for one muscle in a specific movement is optimal. Under normal condition a motor neuron pool is always influenced by excitatoric and inhibitoric action potentials. Skilled subjects have learned to suppress the **inhibitoric effects**. The same is true in SSC movements. The muscle activation patterns of human leg extensors and the corresponding force-time curves in jumping exercises are a good example for those inhibitory mechanisms. With increasing stretching loads, the initial impact peak in the vertical ground reaction forces increases and concomitantly with this enhancement a clear reduction in the EMG occurs (Gollhofer, Schmidtbleicher 1988). These inhibitory effects serve for a worse regulation of the stiffness of the tendomuscular system. Consequently trained subjects are able to tolerate higher stretch loads. All tested subjects showed this inhibitory effect even though individually beginning from different dropping heights. Trained subjects resist the impact forces much better, whereas less trained subjects were affected even from the low dropping height of 24cm. After a systematic training with drop jumps these inhibitory effects were reduced.

Comparable results occur in case of fatigue. If the subjects are in a fatigued state inhibitory influences appear from low dropping height. When drop jumps from a given falling height with constant frequency, i.e. number of jumps per minute are exercised until exhaustion, inhibitory effects can be detected after a less number of jumps (20-30). Well trained subjects are affected after more than 150-170 jumps (Frick 1993). The reduction in the surface EMG is not correlated to lactate concentration. It seems that both effects that occur with fatigue, a reduced metabolic capacity and a neuronal fatigue, cause comparable tendencies in the biomechanical parameters: changes in joint amplitudes of hip, knee and ankle angles and a prolongation of the ground contact time.

In most patients immediataly after injuries or after operation we could find comparable surface EMG-pattern as described above. One could argue that the inhibition is due to the pain but in some of the patients the injury happend some years ago, for example in ACL-rupture, and there was no pain before arthroscopy and immediately after because the subject was still anaesthetized. But even when the patients maintain to feel no pain they show an affected innervation pattern.

Rapp and Gollhofer (1994) reported experiments in which the subjects had to perform drop jumps from different dropping heights in a blindfolded state.The dropping heights were varied randomly and the subjects did not know from which height they should jump down. Under these conditions the registrated EMG-patterns are comparable to those under fatigue, overload, injured and untrained conditions.As long as the subjects have either no correct visual information or no knowledge about the correct dropping height, they are unable to develop a well coordinated innervation pattern. When the subjects are still blindfolded but informed about the real dropping height they are able to compensate the visual informations with other sensoric systems.

All situations in which inhibitory influences can be detected must have a common denominator. Especially the results from the patients and the learning and training experiments indicate, that energetic deficiencies are not responsible for the inhibitoric effects. A common denominator for all described situations is the lack of sufficient information about the expected proprioceptive results or with other words an incomplete afferent set. With an incomplete afferent set humans are not able to develop a correct imagination of a movement in advance and therefore the motorprogram is of minder quality. Instead of optimal intramuscular coordination the typical innervation pattern of the SSC movement is interrupted from inhibitoric influences which are triggered with a powerful activation of the tibial muscle. This coactivation of agonist and antagonist muscle serve for an adaequate stifness of the ankle joint simultaneously diminishing the stretch load for the extensor muscles. It was therefore concluded that the described mechanisms are part of the dynamic performance dependent reaction, functionally serving as a protecting system.

Up to now another variation in the strengthening process in rehabilitation is only seldomly investigated: the **combination of muscle actions**. Two examples may demonstrate the importance of this topic.The first investigation deals with the reflection of the adaptations in neuronal and muscular variables following eccentric exercises. Based on the consideration that best results in hypertrophy of muscle can be achieved with training methods that can be characterized as stimulus configurations with long lasting stimulus duration by a submaximal intensity. And additionally orientated at the knowledge, that very good results in the adaptation of the nervous system can be performed by high intensity stimuli with eccentric muscle actions, a specific training and measurement device was constructed that allowed the application of a combined combination of muscle actions. Starting with a concentric isokinetic movement an isometric phase follows, after reaching 80% of the extension position in the translatoric movement. When 90% of the isometric force level is reached, a hydraulic system pushes the legs against the maximal resistance in an eccentric isokinetic movement back to the starting position. During the whole **cycle of muscle actions (COMA)** the strength never fall short of 60% of maximal voluntary contraction. Therefore the blood supply for the activated muscles was suppressed and the energy deliveration was restricted on the affected muscle only. The aim of the study was to analyse the adaptations caused by a training with COMA. 13 subjects exercised twice a week over a period of six weeks at a special training apparatus.A second group (n=13) worked at a leg press using a simulation of COMA, and a third group served as a control sample. Beside the changes in strength variables muscle cross-section area by computertomography (MCS) and innervation activities (EMG) were observed. The subjects working with high intensitive COMAshowed high significant increase in maximal strength and in EMG-variables (integrated EMG and mean power frequency). No improvements could be detected in rate of force development and in MCS. The subjects of the leg press group achieved only smaller increase in maximal strength and in EMG-variables but higher increases in MCS. The control group finally reached no significant changes in strength and EMG variables but absolutely unexpectant a moderate increase in MCS. All participants of the experiment absolved 10 to 15 hours of physical training, as a part of the physical education study program.

It was assumed that the increase in maximal strength in the first group was due to a longer duration of innervation bursts and that the intensity of the COMA caused two different effects: Firstly a specific adaptation of those mechanisms of the nervous system that are fatigue resistant; secondly one has to interpret that the COMA-stimulus caused catabolic effects. Comparing the stimuli variations between group one and group two, the main differences consist in the eccentric part of the COMA. In group one the apparatus "produces" a supramaximal eccentric muscle action, whereas in group two the eccentric phase of the COMA was submaximal.

Finally the results lead to the conclusion that one should reflect about the intensity and the frequency of training in high performance sports as well as in rehabilitation process.

The second investigation to the combination of muscle action deals with an experiment in rehabilitation, which was based on the consideration, that it might be useful to stimulate the neuromuscular system with a combination of isokinetic concentric and eccentric muscle actions. Therefore the purpose of the study was to compare the effects of a 4 week strength endurance training program of two groups of patients, one using pure concentric muscle actions and the other using a combination of eccentric-concentric muscle actions. 18 male patients with former knee injuries volunteered in the study. As part of their rehabilitation program they underwent the training regimen to enhance strength endurance of the hamstring muscles. The subjects were matched into two parallelised groups. Group one exercised pure concentric, group two eccentric-concentric muscle actions on an isokinetic device (KIN COM H2). During the 4 week training period 3 training sessions per week were performed. Each session consisted of 3 sets during the first two weeks and of 5 sets for the next two weeks. Rest intervals between sets were 1 minute. In each set 30 concentric (group 1) or 15 eccentric-concentric muscle actions were executed. The movement velocity was 60% and the intensity about 40% of the individual isometric maximum. The range of movement varied from 0° (knee extended) to 90° knee-angle. In pure concentric conditions the device extended the knee passively back to starting position, while hamstring muscles had to work continously until the end of the set in the eccentric-concentric group.

At the begin, after 2 weeks and after 4 weeks of training the following test procedure was registrated: 30 concentric, 30 eccentric and 15 eccentric-concentric muscle actions. Additionally the isometric maximal strength of the hamstrings was measured, heart rate and blood samples were taken for the determination of lactate, triglyceride (TG), cholesterol (CH), urea (U) and creatine kinase (CK).

The results of the test at the begin of training indicate, that also for isokinetic conditions the mechanical load of the tendomuscular system, the work eficiency and the metabolic demands are strongly influenced of type of muscle action.

Total work is significantly higher under eccentric compared to concentric or eccentric-concentric conditions. The opposite is true for the maximum lactate concentration and the heart rate. During the training period both groups enhanced their strength endurance significantly. The benefits of training were greater during the first 2 weeks compared to the second two weeks and the increase in strength endurance showed best results in the specific trained muscle action.The fatigue induced reduction of work output during the testprocedure was the same in pre-,middle- and posttest. In the maximum lactate production the groups showed differences: while group two (eccentric-concentric) increased lactate slightly throughout the whole training period, group one (concentric) reduced lactate during the first two weeks and than enhanced it during the following period. Both groups showed no significant longterm efects on the biochemical parameter of CK, U and CH. The triglyceride levels of group two were significantly enhanced after 4 weeks of training, these of the subjects with concentric training only (group one) were unaltered.The gain in strength endurance after the first 2 weeks of training should originate from a better intra- and intermuscular coordination mainly (Sale, 1992).A better coordination should cause a more efficient workout. The enhanced relation of total work and maximal lactate during the first 2 weeks confirm this assumption. During the following period this relation remained unchanged or was reduced. Therefore the improvements in strength endurance and in maximal strength should not originate from a better coordination, mainly, but from an adapted metabolic capacity. The unaltered levels of most of the biomechanical parameter are going well together with the results of other authors (e.g.Tesch 1992). In a summarized consideration the training regimen using eccentric-concentric muscle action was more efficient in the improvement of strength endurance and in maximal strength and therefore should be preferred. With respect to the number of sets per training unit one should remind that the increase from 3 to 5 caused minor gains and was therefore less efficient (Frick, Schmidtbleicher, 1995).

A further way to improve movements results from better**intermuscular coordination**. Intermuscular coordination describes the ability of all muscles involved in a movement: agonists, antagonists and synergists, to cooperate wholly with respect to the aim of the movement.This type of adaptation is therefore movement specific and not transferable to another movement. One should take into account that if performance of movements of daily life are intended, exactly these movement must be skilled. Very often general exercises in rehabilitation training are used with the hope to gain transferable adaptations. Normally the patients achieve a success in the trained general exercises but show only moderate improvements in the movements of daily life.

Adaptation of maximal strength, power and strength endurance requires less ore more time, depending on the quality and quantity of the training.

The first adaptations are always mainly of an intermuscular coordinative nature and the first stabilization of training effects appear after 2 weeks, by four training units per week. Neuronal adaptations of the intramuscular type lead after 6-8 weeks (again four training units per week) to farreaching compensatory modifications, especially in power and strength endurance production. However, only the increase of muscle mass offers considerable improvement in maximal strength and therefore also in power and strength endurance. Experience, as well as investigations from Häkkinen et al. (1988) indicate that after approximately 9-12 weeks of training, related to the type of training and sex of subjects, the rate of increase drops of dramatically. Based on this knowledge, it is indicated that one should use another hypertrophy method or emphasize changing to another type of training stimulus, i.e. geared towards the neuromuscular system.

The described results, as well as practical experience, allow a rough classification of training methods with respect to this physiological adaptations. Based on these considerations a model for the step-wise periodisation of the training process in rehabilitation can be developed.

PHASES IN NEUROMUSCULAR REHABILITATION AFTER MUSCLE, LIGAMENT AND BONE INJURIES

First conceptual proposals for a phase orientated organisation in muscular rehabilitation were presented from DeLorme and Watkins (1953) and from Hettinger (1968). In the older concepts isometric muscle action played a basic role, whereas nowadays the phases of training and the muscle actions are more diferentiated (Grimby 1992).

First activities are indicated for those patients who need an **immobilisation**. To avoid or minimize atrophy, isometric maximal and submaximal muscle action as well as electrical muscle stimulation (EMS) is recommended.The stimulus intensity should be about 60-80% of maximal voluntary contraction (MVC) and the stimulus duration should not exceed 10 minutes. If the stimulus configuration trends to perform the strength endurance, the intensity is to low and the duration to long. In that case one would support the atrophy of the fast twitch fibers (FT II B) which are mostly affected anyhow. Of course isometric contractions and EMS are possible only if they do not cause pain. After 4 weeks patients without those activities have reduced MVC to about 40%, patients with training only to 70%.

Before starting with a muscular training in some patients **preparatory phases** are necessary. As described above some subjects have disturbancies in their aferent sets and therefore an incomplete proprioception, which causes difficulties in planing and generating "normal" movement programs. In single patients the ischemia during the operation led to serious damage of the efferent and afferent axons so that long lasting disturbancies prevent muscular adaptation in a strength training.Therefore it is neither useful nor indicated to start with a muscular training without an intact afferent set.

Depending on the grade of atrophy some patients have to make themselve familiar with skills that serve for an increase in the range of movement and improve the strength endurance in a manner that at least 20 workouts are possible.

The initial efforts in a muscular training are directed to the **removal of the atrophy**. Those hypertrophy methods are characterized by a large number of sets (3-5), with repetitions between 12 and 15 with an intensity of about 70% MVC.The execution of the movement is slow and a training session should end with a complete failure. Rest intervals between sets are about 2 minutes to get an additive depletion of the energetic phosphates. Normally this training procedure will be continued until the affected muscle or muscle group has reached the level of the comparable muscles on the lateral side of the body. It should not be forgotten here that also the unaffected muscles show reduced strength levels in a range of about 20%. Mostly in this stadium the rehabilitation process is finished.

Without any doubt there have to be installed a consecutive training that is directed to the **adaptation of the nervous system** with the purpose to increase the **rate of force development**. The main characteristics are short-term extremely fast maximal action against near maximum loads, or in case of eccentric actions against supramaximal loads. Difficulties in understanding the demand of the "extreme fast actions against high loads" occur if one does not differentiate precisely between contraction and movement velocity, i.e. the contraction velocity is high at the begin of the contraction but the movement velocity is slow because of the high loads.These RFD methods are characterized by 3 sets with 3 to 1 repetitions each, an intensity of 90% MVC or more and rest intervals between the sets of at last 5 minutes to avoid neuronal fatigue.

The next phase encompasses all activities that are suitable to increase performance capabilites in **stretch-shortening cycle movements (SSC).** All SSC methods aim primarily at adaptations of the nervous system.Therefore, they should only be performed in a rested state. For patients the use of steps, double and single leg hoppings are indicated. In daily life SSC occur in movements stepping downstairs (i.e. leaving busses, trains and rails).These strains are between 1.5 and 3.5 of body weight depending on the stepping height.The strength endurance orientated number of SSC should be about 30-50 continously performed workouts.This is comparable to the number of steps on stairways at railway stations, which one had to overcome moving from one platform to another. A prerequisite for the begin with a SSC training is the ability to develop a maximal strength in a single leg test, that is according to 1.5 body weight.

In the last phase original movements of daily life, or in the case of athletes training and competition specific movements have to be skilled.Those **coordination effects of the intermusculare type** are highly specific and permit no transferable benefits to other movements. The aim of this part of rehabilitation is reached when the subjects are coming back to an unrestricted movement, including a fully confidence even in critical situations. For athletes, this phase ends successfully when they have increased their stress tolerance and performance capability by systematic training, beyond the level at which the injury happened.

An orientation of the rehabilitation process on the presented results and considerations will on one hand probably increase the duration of rehabilitation, on the other hand the number of reinjuries will be considerably reduced.

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