APPEARANCE OF EFFORT-DEPENDING CHANGES IN STATIC LOCAL FATIGUE

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Relationship between appearance of some effort-depending symptoms and local subjective fatigue was investigated in sustained elbow flexion. Exertion at 30–60% of the maximum strength was performed until exhaustion by ten male adult subjects in sitting posture. Local pain appeared on the average at 0.30, 0.36, 0.40, and 0.45 of the maximum endurance time for 30, 40, 50, and 60% contraction, respectively. The average deviation of the muscle force, heart rate, and pulmonary ventilation increased gradually as local fatigue developed. Significant increase of integrated surface electromyogram of the biceps brachii was evidenced by a trend test made somewhat before the onset of local pain. The appearance of effort-depending symptoms, such as increase of synergistic activities or changes in foot pressure, took place when distinct local pain was present. Then some changes in facial expression followed. Breath-holding strain with general muscular tension was usually observed in the latter part of the endurance period, at 47–98% of the maximum endurance time. As the contraction intensity increased, the effort-depending symptoms, except breath-hold strain, seemed to appear earlier in relation to endurance duration, but the order of their development was always consistent. Their relation to local fatigue, especially to the onset of local pain, was discussed.

It has been shown by many authors that an isometric load-endurance relationship is a useful indicator of the endurance capacity of a concerned muscle group (Rohmert, 1960; Monod and Scherrer, 1965). Local as well as general fatigue-induced symptoms developing in the course of sustained endurance situations

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have also received attention as criteria of early fatigue since, Cobb and Forbes (1923), Merton (1954), and others revealed that local fatigue is measurable in physiological terms. Park and Rodbard (1962), Kogi and Hakamada (1962), Caldwell and Smith (1966), and Kogi (1970) suggested local muscle pain as a subjective criteria of local static fatigue, and our previous has study shown that spontaneous protective action against muscular fatigue, such as alternation of the active limb, does occur in relation to subjective fatigue, possibly preceding the onset of local pain (Tanii et al., 1972). When contraction is sustained disregarding those initial signs of local fatigue, the continuing effort seems to extend its effect to all body organs. Any sustained contraction gives rise to respiratory and circulatory changes indicating a deterioration of a steady state which can be used as a correlation of the loading (Rohmert, 1960; Lind et al., 1964; Bartels et al., 1968; Lind and McNicol, 1968). It must be noted, however, that usual metabolic and circulatory changes are results of a combined effect of local metabolic changes in the acting muscle and associated efforts. This makes the interpretation of the data with respect to enlarged effort difficult, most of the data changes slowly gradually during the period of endurance. Horiiuchi (1956) and, recently Sanjö (1971) reported that synergistic activities are seen also in the early periods of isometric contractions. Such qualitative changes would be more effective in elucidating the propagating effort.

It may then be reasonably assumed that a certain underlying neural mechanism works in exhibiting those effort-depending changes and that these changes may produce certain consistent results that play a role in the cessation or continuation of the endurance situation. Sasaki (1969) and Davis and Troup (1964) paid attention to the breath-hold strain in the case of submaximal isometric pushing and pulling, but how such extended strain is responsible for medium intensity endurance remains unanswered. Experiments were therefore performed to examine the relationship between effort-depending changes and the subjective indications of local fatigue. Some evidence presented in this paper favors the consistency of effort-depending changes in local endurance experiments.

**METHOD**

Sustained elbow flexion of the right arm, the upper arm being held horizontally on a table, parallel to the sagittal plane, and the holding of the forearm vertically and supinated were performed in a sitting position on a chair by ten healthy male adults, 22–42 years old.

Muscle strength exerted in the arm position was measured by means of a strain gauge method. An aluminium plate, 5 × 11 cm, curved to suit the palmar side of the wrist and covered with soft foam rubber was fixed in the center of the load cell carrying the strain gauge, so that the force exerted toward the subject could be measured. The height of the plate from the table was adjusted to
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the elbow-wrist distance of each subject. After the maximum possible strength was obtained at this arm position for each subject, isometric contraction was sustained until exhaustion at load intensities of 30, 40, 50, and 60% of the maximum strength. Each subject underwent only one endurance test per day. The exerted force from the prescribed level was displayed by a horizontal line on a cathode-ray tube placed in front of the subject. The average deviation was computed by integrating the sum of the absolute deviations for every 15 sec period.

The subject was instructed to report the grade of subjective local fatigue feeling by means of finger signs with the left arm which hung loosely at the side. Local fatigue was rated in four stages: grade 1, the initiation of any slight local fatigue sensation; 2, onset of local pain in elbow flexors; 3, moderate local pain which could be distinctly felt in the flexor region; 4, intolerable pain.

A cumulated pulmonary ventilation curve indicating each tidal volume and its intervals was recorded on a spirometer by gathering expired air through a mask. Electrocardiogram was recorded with chest electrodes to calculate the heart rate from distribution of R–R durations. Foot pressure on a horizontal iron bar 4 cm in width and set apart from the floor was recorded continuously by the strain gauge technique, and a printer printed every second the digitalized output of the strain amplifier. The facial expression of some subjects was filmed with a 16 mm motion camera.

The surface electromyogram of the right biceps brachii and brachioradialis was bipolarly led and recorded on a magnetic tape with a time constant of 0.03 sec. Its absolute value was then integrated and the integrated value was converted to pulse signals. The number of pulses per second was printed out to indicate the integrated EMG for each second. The data of the EMG of the brachioradialis and the spirometer were obtained for only five subjects.

About 3–4 ml blood from the v. mediana antebrachii was sampled during rest and after exhaustion for 30%, 50% and preliminarily tested 70% contractions, and the pH and the lactic acid concentration of the blood were determined. The pH was determined immediately after sampling of the blood by a glass electrode and the lactic acid of the blood by method of enzymatic analysis.

RESULTS

Local pain and maximum duration

Table 1 shows for different load levels the time of onset of local pain in the elbow flexors, and, in parentheses, the maximum endurance time. As the table shows, the time of the appearance of local pain varied considerably among subjects. If it was indicated as a quotient of the maximum endured time, its mean was 0.30 of the latter for 30% force sustenance, 0.36 for 40% force, 0.40 for 50% force, and 0.45 for 60% force. The average exhaustion time was 456, 239, 138, and 92 sec for load intensities of 30, 40, 50, and 60% of the maximum strength,
Table 1. Time of onset of local pain and maximum endurance time (in parentheses) for different contraction intensities of ten subjects.

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<th>Subject</th>
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respectively. The changes after exhaustion for venous blood pH and lactic acid concentration obtained for two subjects were considerably large, as illustrated in Fig. 1. The pH decreased from the resting value of 7.46 on the average to 7.10–7.38 immediately after exhaustion. The concentration of the lactic acid in venous blood increased after exhaustion from the resting mean value of 19.1 to 53–86 mg/dl, which was maintained for several minutes.

Changes of motor control, heart rate, and pulmonary ventilation

Figure 2 indicates the means and ranges of standard deviation for ten subjects of the control errors, i.e., average deviation of muscle force from the given level, for each stage of local fatigue. In the case of the 30 or 40% load, the control errors increased only when severe pain was present. They began to increase in the earlier stage of local fatigue in the case of higher loads with 50 or 60% force. It was thus revealed that the motor control was well maintained at stages 1–2 of local fatigue, as compared with the marked increase of the deviation in later stages. The two factors analysis of variance on the control error and the contraction sessions proved that it was significantly different both among load levels as well as among fatigue stages (P<0.01, respectively).

Gradual heart rate increase for different stages of the advancement of the
local fatigue for the four load levels is shown in Fig. 3. At the first stage of feeling fatigue, the mean heart rate was nearly the same for all of the four force levels, but the heart rate difference between lower and higher forces became significant as the local pain appeared and increased. A mean difference of more than 20 beats/min was seen between the 30 and 60% force for the time when intolerable pain was experienced. The mean heart rate at time of the exhaustion was 98, 106, 103, and 112 beats/min, respectively, in the order of the load intensity.

Changes in pulmonary ventilation curves at rest during the sustained contraction of four load levels are demonstrated for two subjects in Figs. 4a and 4b. The numbers given under the abscissa indicate elapsed time from contraction onset. The height of each spirometric curve shows the pulmonary ventilatory volume for one minute, each tidal volume being shown by stairwise steps. The horizontal length of each step shows the interval between expirations. Arrows indicate the point of exhaustion. Longer horizontal lines indicating breath-
Fig. 2. Changes of blood pH (upper diagram) or of blood lactate concentration (lower diagram). A: at rest, B: immediately after exhaustion, C: 5 min later, D: 10 min later.

holding with strain are frequently seen in the last stages of the contraction. Pulmonary ventilation often became smaller than that of the resting period for about a half a minute period from the beginning of contraction. Afterward the slope of the spirogram became steeper, showing that pulmonary ventilation gradually increased. It is also shown that an increase of pulmonary ventilation became more remarkable with load increment. As the respiration revealed more definite changes in the latter half of the endurance period, the tidal volume obviously fluctuating, breath-holding began to appear for all force levels investigated. Breath-holding usually appeared in the last part of the endurance period in a series, the mean pulmonary ventilation resulting in a marked decrease. Breath-holding in the latter periods was characteristically accompanied by simultaneous exertion of a wide range of muscles. This could be ascertained by recording of EMG, ECG, foot pressure measurements and direct observations.
Fig. 3. Heart rate levels at rest, at different stages of local subjective fatigue, and at the exhaustion for different contraction intensities. Bars indicate plus or minus standard deviation of the mean.

Fig. 4a. Spirographic recordings of subject 3 before and during isometric elbow flexion at 30, 40, 50, and 60% of the maximum strength. R, at rest; 0, beginning of the contraction; 60, 120, etc., time in sec after the beginning of contraction. Arrows show the exhaustion point at which the subject stopped contraction.

For reference this type of breath-holding will be described as breath-hold strain. After cessation of static contraction, hyperventilation occurred in all cases of various load intensities. The 16 mm-film records made during the experiment showed that the facial expression of the subject changed from an ordinary expres-
sion to a frowning and seemingly painful one usually after he indicated distinct local pain. A few subjects showed the similar expression only when they had intolerable pain.

*Relation of effort-depending symptoms to local pain*

Figure 5 illustrates changes until exhaustion of the integrated values of surface electromyogram of the biceps brachii of two subjects. The integrated EMG was averaged for each three-second period in case of 30 and 40% load, and for each second in case of 50 and 60% load. Arrows in the figure indicate the point when the increase of integrated electromyogram was first evidenced by a non-parametric trend test at the significance level of 0.05. The same test was also applied to the EMG of the ipsilateral brachioradialis, and in all cases the increase of the EMG of the biceps proved to be earlier than that of the brachioradialis.

Figure 6 summarizes the cumulative curves of the onset time of different degrees of subjective local fatigue feelings and those of the point of time where each of the effort-depending symptoms just appeared for the 30, 40, 50, and 60% contraction levels. The abscissa indicates the relative duration of contraction in a quotient of the maximum endured time for the concerned contraction intensity of each subject. The increasing point of the EMG of the biceps or the brachioradialis was determined by the above-described trend test. The point of time where the breath-hold strain first appeared was determined by referring to both the spirogram and the respiration curves recorded by means of thermister technique. Since the breath-holding with strain lasting for several seconds always occurred in the inspiratory phase, and the increase of the general muscular strain could be evidenced on electromyographic and electrocardiographic recordings, the determination of the breath-holding strain was not difficult. In the case of
Fig. 5. Changes of the integrated value of surface EMG of the biceps brachii of two subjects. Ordinates indicate the relative integrated value in % of that of maximum contraction without fatigue. Arrows show significant increase of the integrated activity evidenced by trend test.
60% contraction, temporary breath-holding was observed in a very early period for a few subjects, but these were excluded from the illustration because they appeared only temporarily, without general strain, and were followed by a period of steady respiration. The change in foot pressure, which was in most cases an increase of the sum of the pressure of both feet, referred to the point of time in which the digital reading of the pressure became outside the mean plus or minus three times of the standard deviation for the first 15 sec period after contraction start.

As shown in the upper diagrams, the onset of each degree of subjective fatigue feeling was generally earlier in relation to the maximum endurance time for 30 or 40% load than for 50 or 60% load. It was also the case for the onset of muscle pain, as mentioned above. The moderate but distinct local pain was recognized around the half way point of the maximum endurance time, its distribution ranging towards the latter part of the endurance for higher forces. Intolerable pain was found for most subjects in the 0.70-0.90 of the maximum
endurance time, though a few subjects complained at around 0.50. The period of intolerable pain was thus well correlated with the individual endurance duration. In the case of the 30% load intensity, the increase of the integrated values of surface electromyogram of the biceps brachii was plotted near the first grade appearance of local fatigue sensation, while that of the brachioradialis was at the time of appearance of moderate local pain. Breath-holding with strain appeared only after intolerable pain was present. The change in foot pressure was scattered around the appearance of local pain. When the load intensity increased to 40% of the maximum force, the increasing point of the biceps EMG seemed to be delayed, while the time when the foot pressure significantly increased was earlier. But, in the 50 and 60% loads, the order of the appearance of the effort-depending symptoms was again similar to that in 30% load, the initiation of the increase of the biceps EMG being roughly between appearance of local fatigue sensation and onset of local pain. The increase of integrated electromyogram of the brachioradialis and the change in foot pressure were approximately plotted around the time of appearance of local pain. The breath-holding reaction with strain was in good correspondence with the appearance of intolerable pain, ranging from about 0.60-0.90 of maximum endurance time. In several cases of the 50 and 60% contractions, the increase of surface electromyogram of the biceps brachii was observed in a very early period in relation to the maximum endurance time, even earlier than the appearance of local fatigue sensation.

Thus, the range of the breath-holding with general muscular tension was almost identical for the four contraction intensities, usually beginning in the latter half of the contraction, from 0.47 to 0.98 of the endurance time. A tendency may be observed in the effort symptoms, except breath-hold strain, appearing much earlier in relation to the endurance duration. They seemed to appear sooner as the contraction intensity increased. The increase of amplitude of surface electromyogram of the biceps brachii, the main contracting muscle, preceded them, taking place before or just after local fatigue sensation was felt, except for foot pressure change in 40% contraction. The brachioradialis, a synergist of the biceps, increased its electromyographic amplitude approximately at the time of the appearance of slight or moderate local pain. Foot pressure change was seen roughly at the time of appearance of local pain. It is suggested from the results that the effort-depending changes gradually extended after local pain appeared from the local contracting area to other regions of body, finally to lead to general muscular strain with intermittent breath-holding.

**DISCUSSION**

The present data confirm the relationship between feeling local fatigue and the propagation of effort-induced tension of other body parts in maintaining localized static contraction. With the advance of local fatigue sensation and
muscle pain, increased synergistic activity, change of the working position, facial expressions suggesting increasing efforts, and breath-holding strain were observed to commence step by step as the local fatigue developed.

The effort to maintain the contraction is naturally assumed to be larger as the sustained intensity for the given muscle group increases, but our results show that each of the changes relating to effort had a fairly consistent relationship to the maximum endurance time, irrespective of the contraction intensity. In particular, repeated breath-holdings with strain were always seen to commence in the last period of the endurance, suggesting that effort to sustain the contraction led finally to an extraordinary exertion of many non-relevant muscle groups of the trunk.

A sustained load produces pain-inducing metabolites in the contracting muscle, generating a painful, subjective feeling which increases almost linearly with the accumulation of the metabolites (Park and Rodbard, 1962; Caldwell and Smith, 1966). A relatively early onset of the pain, as suggested by Kogi and Hakamada (1962) and Caldwell and Smith (1966), necessitates a long sustenance of painful contraction until the local sensation brings the exercise to a halt. Breath-holding characteristic to the sustaining effort was noticed by Horiuchi (1956), Morioka (1964), Sanjō (1971) and others. This is so prominent that the pulmonary ventilation may be temporarily reduced as also confirmed by the present experiments. Few studies are available, however, concerning the relation between local pain and contraction-sustaining efforts including breath-holding. Horiuchi (1956) and Sanjō (1971) reported on the gradual participation of muscles other than the original active muscle, the latter author suggesting that the participations of the contralateral muscle groups pertain to a certain degree of fatigue in the main active muscle. In maintaining isometric contraction, local fatigue processes associated with accumulation of pain-inducing metabolites may be evidenced to proceed gradually from the very beginning of contraction as suggested by reduced muscle blood flow, amplification or slowing of the surface electromyogram, increase of heart rate and pulmonary ventilation, or gradual increment of local pain. Nevertheless, significant behavioral changes in the subject are not usually observed during the early period and seem to appear only when some fatiguing changes in muscles and relevant neuronal mechanism have taken place. Thus the apparently severe reaction with general strenuous efforts, including breath-holding, proved to be in good correspondence with the sensation of intolerable pain specific to the last period of the endurance. Fluctuation of the tidal volume was always apparent in that case. It should be noted that the breath-hold strain was observed in a similar relation to the maximum endurance time for all levels of contraction intensity investigated. The application of moderate contraction intensities of 30–60% maximum force may account for the rather stable appearance of the breath-hold strain. That the subjects endured well until exhaustion in these experiments may be also indicated by considerable significant
reduction of the venous blood pH and increase of the blood lactate for both lower and higher load intensities. MORIoka (1964) reported that the decrease of respiration rate was observed frequently in final period and that subjects explained after the exercise that the tension was maintained barely by choking breath in the inspiratory phase. SANJO (1971) also reported that breath-holding was a part of the general muscular tension by which the subject endeavored to continue.

LLOYD (1970) carried out a study on the subject's assessment in muscle fatigue, and reported that the endurance time during which there was no significant increase in amplitude of electromyogram of the active muscle was interpreted to be the time during which localized recruitment of the motor units was sufficient to maintain the necessary tension level. The point in time when the amplitude of electromyogram significantly increased was suggested as the point of localized fatigue of the active muscle where additional conscious effort was necessary to sustain the required tension level. The onset of local pain, the median time of which ranged in our experiments between 0.30 and 0.45 of the endurance time for four force levels, seemed to be preceded by a significant increase of electromyographic activity of the main active muscle, the biceps brachii. It can be reasonably assumed that this is accompanied by some increase of slower components in its frequency spectrum, indicating an advance of local fatigue. The question that then comes to mind is in what manner are other changes, indicating the increase of the exercise effort, to be observed during the period between the first evidences of fatigue of the active muscle and the overall strain with breath-holding. The findings of SANJO (1971) that in sustained elbow flexion the tension of contralateral arm muscles appeared regularly following local pain of the active flexors correspond with our results. The changes in foot pressure was recorded around the point of distinct biceps pain, with exceptions of the 40% load. Since the foot pressure usually increased while the foot position was constant, the observed changes will be a function of the effort to maintain the exerting force. The propagation of the effort to non-relevant muscle groups under moderate pain may be also shown by the changes in facial expressions which are seen as a rule essentially earlier than the breath-holding phase.

The interpretation of the increase in the electromyographic activity of the ipsilateral brachioradialis, a synergist to the brachial biceps, needs further examination, since it means either or both increased participation and/or fatigue. The fact that its changes were delayed to a considerable extent compared with the changes of the biceps, roughly corresponding to the sensation of distinct pain in the biceps region, would be at least suggestive of its increased participation due to the biceps fatigue.

From the results of the present paper and SANJO (1971), and referring to the conception mentioned by LLOYD (1970), it may be assumed that after a certain degree of fatigue of the active muscle the sustaining of isometric effort necessitates participation of synergistic, antagonistic, position-maintaining, and other muscles
of limbs and trunk in a certain form and that the propagation of the muscular tensions is consistent with respect to their order and to the time of their appearance in relation to the maximum possible duration. Intolerable pain which brings the contraction to a halt will produce repeated breath-hold strains during inspiratory phases.

Masuda and Shibayama (1969) reported that when gripping was made with maximum effort it was maintained in all the subjects at the inspiratory phase, and that the exertion was initiated generally within the last one-third of the inspiratory phase. It seems that such a kind of effort appears for moderate degree of static contraction only in the final period of endurance where an excessive effort is needed to compensate for the reduced contractility of the active muscles. Morris et al. (1961) reported that the increase of trunk muscle activities was to promote intracavity pressure. Sasaki (1969) further noted that intense pushing or pulling could only be executed by simultaneous contractions of trunk muscles, thus resulting in increase of intrathoracic and intra-abdominal pressure. He suggests this purposeful increase of pressure has a demoralizing influence, being accompanied with temporary but complete breath-holding. If the main arteries and veins as well as the pulmonary capillaries are pressed by increased intrathoracic pressure (Oda, 1955), venous return to the heart is restricted (Toyoda, 1964). The increased heart rate was solely responsible for the increase in cardiac output (Lind et al., 1964), presumably in an attempt to maintain perfusion of the muscle where mechanical compression threatens to restrict the blood supply. The mechanism may account for the pronounced increase of heart rate in phases of intolerable pain with breath-holding in the present experiments. This might be also a reason for the heart rate not necessarily reflecting the degree of fatigue in static local effort as suggested by Hansen and Maggio (1960), Carlsten and Grimby (1966), Morioka (1964), and Burger (1969).

If, however, even a moderate increment of local pain works to manifest increased tension in various muscles, the associated efforts will accelerate induced fatigue. The propagation of effort-depending symptoms will doubtlessly contribute, in addition to the pain in the active muscles, more or less to the intolerableness of continuing the contraction.

The authors' previous results that the spontaneous alternation of the raised arm took place before distinct local pain appeared suggest the importance of the earlier signs of fatigue by which the subject may conduct himself to avoid the impairing effect of advanced fatigue. Because the time course of the electromyographic changes, heart rate, or mean pulmonary ventilation is essentially continuous and not therefore effective to elucidate such qualitative signs of earlier fatigue, more attention should be paid to slight and moderate muscle pain, and propagated changes seen around the onset of local pain which depend upon the generalization of effort.
REFERENCES


