Local Muscle Fatigue

Learning Objectives

- Define local muscle fatigue and aspects of work task that may lead to increased fatigue (or decreased endurance)
- Estimate endurance times for a static task, and determine methods to maximize endurance (or minimize fatigue)
- Describe how fatigue/endurance are influenced by task and individual differences
- Describe the potential utility of local muscle fatigue in ergonomic assessment and design
- Summarize important limitations in current knowledge with respect to the ergonomic application of local muscle fatigue (e.g. measurement, guidelines, etc.)
Fatigue

• Whole-Body Fatigue
  – overload of metabolic (aerobic) capability
  – short-term capability = AC
  – long-term capability = PWC = f(AC,time)

• Local (or Localized) Muscle Fatigue (LMF)
  – overload of specific (regional) muscular capability
  – endurance time vs. effort level (earlier)
  – applications in workstation design and layout

• Both types of fatigue are associated with:
  – discomfort, pain, cramping, soreness, dissatisfaction
  – decreased productivity and efficiency
  – increased error rates and decreased accuracy
  – increased injury rates (mechanism?)

Localized Muscle Fatigue

• Strength is a maximum short-term effort (defined as a joint moment or an external force)
• Endurance is longer-term: time to exhaustion (fatigue occurs early)
• Fatigue: any work- or exercise-induced reduction in the capacity to generate physical output (e.g., force, moment, power)
  – During prolonged or repetitive work of sufficient magnitude and duration, capacity steadily declines
  – Fatigue is thus a continuous and ongoing process
• Endurance time and fatigue vary with exertion level (e.g., % of maximum capacity)
• Endurance and fatigue are thus a function of the load (or effort) and posture
• Endurance ≠ Fatigue
Endurance vs. Fatigue

Effects of LMF

- Physiological
  - Decreased muscular strength and endurance
  - Changes in intra-muscular biochemistry (e.g., pH, Ca^{2+})
  - Changes in electrical activity (EMG)
  - Recovery time depends on exertion characteristics
- Subjective
  - Sensations of discomfort, weakness, pain
- Performance-related
  - Decreases in accuracy and fine control; tremor
Local Muscle Fatigue

Measuring LMF

• Physiological
  – Strength and endurance
  – Intra-muscular pH, lactic acid, oxygenation, perfusion, ...
  – EMG amplitude and spectral distribution

• Subjective
  – Perceptual assessments (pain, discomfort, …)

• Performance-related
  – Accuracy, repeatability, speed, errors, …

State of Knowledge on LMF

• Known (mostly)
  – Responses to prolonged static loads
  – Broad effects of regular rest breaks
  – Metabolic (biochemical) responses

• Unknown (in general)
  – Responses to realistic loading conditions
  – How to characterize complex loading
  – Best measures of LMF and inter-relationships
  – Intra- and inter-individual differences
Endurance Time vs. Exertion Level

Endurance Time vs. Exertion Level, contd.

- Estimating endurance time for **static** exertions
  \[ T = \frac{1.2}{(0.01f - 0.15)^{0.618}} - 1.21 \] (\( T \): minutes; \( f \): % MVC)
  - Niebel and Freivalds, 1999
  - *Note:* only for \( f > 15\%\)MVC (and not accurate \( \approx 100\%\) MVC)
  - 50\% MVC \( \Rightarrow \) 65s
  - 70\% MVC \( \Rightarrow \) 32s
- Endurance time is **not** infinite for \( f < 15\% \) MVC
- Large variability within and between individuals
Effects on Endurance Time

- Shape and location of endurance curve can vary with:
  - muscle group (e.g., soleus vs. gastrocnemius)
  - age (fitness maintenance)
  - endurance training (low force, high reps)
  - strength training (high force, low reps)
  - static vs. dynamic work

\[
\text{Exertion Level (%MVC)}
\]

\[
\text{Endurance Time (min)}
\]

Variability in Endurance Time

- Maximum endurance time (MET) as a function of relative effort (%MVC)
- Dashed line = 15\textsuperscript{th} percentile
- Substantial variability between studies
- Differences between muscle groups (may be related to differences in fiber type composition)

From El ahrache et al. (2006) IJIE 36:99-108
Local Muscle Fatigue

Endurance Time Varies between Muscles

- Comprehensive analysis across body regions
- 194 publications, 369 data points
- Power functions -> best fit to experimental data
- Significant differences between pairs of joints
  - ankle > trunk > hand/grip > elbow > knee > shoulder
- A single model is not adequate


Muscle Fatigue and Rest Periods

From Chaffin et al (2006) Occupational Biomechanics. Figs. 10.2 and 10.26
Muscle Fatigue and Injury

Sites of Muscle Fatigue

- Potential sites of failure during muscular activity
- Almost wherever people look, they find decreases in function
- Specific effects are task-dependent (e.g., static vs. dynamic)

Notes:
- NMJ = neuromuscular junction
- ECC = excitation-contraction coupling
- $Ca^{2+}$ = calcium

From Chaffin et al. (2006) Occupational Biomechanics. Fig. 10.5

Avoiding Fatigue

• Static loads decrease blood flow to muscle (substantial decreases above ~15-20% MVC)

• Loads as low as 4-6% MVC can cause fatigue

• More rapid onset of fatigue with static muscle exertions as compared to equivalent dynamic exertions
  – Decreased blood flow (energy supply)

• Fatigue depends on both demands and capacity!
  – Non-neutral postures can increase demands, and
  – Decrease strength (capacity), hence
  – Decrease endurance

Posture: Moments, Strength, and Endurance

• Substantial shoulder moments result from even small arm abduction angles

• Moment capability of a joint varies with its orientation (mechanical and physiological causes)

• The ability to maintain a fixed (posture) depends on the orientation of the body segments
Head and Arm Static Exertions
During Seated Work

- Time to reach shoulder muscle fatigue will be shorter with increased shoulder flexion and increased hand-held weights
- More rapid fatigue onset with increasing shoulder abduction, especially > 30 deg
- Shorter endurance times associated with increased forward reach distances
- Increasing forward tilt of the head (especially > 30 deg) will cause earlier fatigue onset

Controlling for Static Exertions

- Interspersed rest periods can increase endurance times
- Rest periods, though, will be relatively ineffective for strenuous exertions (80 - 100% MVC)
- Minimize joint moments. Even small extremity deviations will result in high moment loads
- Minimize reach distances to minimize joint moments
- Maximize strength by keeping objects close to the body
- Maximize capacity by using larger muscle groups and postures that are near the middle of the range-of-motion (length-tension!!)
Minimizing Muscle Fatigue

- Work-rest cycles
  - short and frequent may be best (though limited supporting evidence)

- Decrease magnitudes of static or sustained loads
  - decreased moments -> decreased muscle forces
  - work upright and keep objects close

- Support body segments
  - arm rests
  - lumbar support
  - tool support, holsters, or balancing

- Floor mats
  - some evidence that there is increased blood flow to legs, less impact, decreased perceived fatigue, and decreased leg swelling

Rest Allowances during Static Work

- Rest allowance needed following isometric work
- Allowance given as a function of the holding time
- From Rohmert (1973) *Applied Ergonomics*, 4:91-95
Other Issues in Muscle Fatigue

- Fatigue has been suggested as a risk factor for the development of chronic musculoskeletal disorders, yet the exact causal mechanisms are unknown.
- Fatigue may be a surrogate for other underlying processes:
  - changes in muscle recruitment
  - changes in joint motion patterns
- Both efficiency (time) and effectiveness (errors) are adversely affected when fatigue (subjective or objective) is present.
- Difficult at present to predict or model local fatigue during non-isometric and/or non-isotonic exertions.

Modern Approaches and Research Needs

- Measuring Fatigue
  - EMG-based
  - Near-infrared spectroscopy (NIRS)
  - Performance
  - Perceived discomfort
  - Central vs. peripheral fatigue
  - Low frequency fatigue
- Predicting (modeling) Fatigue
  - Intermittent tasks
  - Individual differences
  - Task characterization
Guidelines

• A need for quantitative guidelines, particularly for realistic work conditions (e.g., non-static)
• Continuous Static work
  – Force-endurance relationship well-described
  – Variable within and between individuals
• Intermittent Static work
  – Similar curves; longer endurance times
  – Similar to many industrial tasks (e.g., assembly lines)
• Dynamic work
  – Changes in muscle length, velocity, blood flow, and tension
  – How to characterize complex tasks (vs. simple %MVC)

Guidelines, contd.

• Continuous work
  – Effort – endurance relationship
  – Acceptable or “Critical force” ~ 15 – 20% MVC
• Intermittent Work
  – Three parameters
    ◊ Workload intensity (contraction level: CL)
    ◊ Work-rest regimen (duty cycle: DC)
    ◊ Work cycle (cycle time: CT)
  – Similar effort – endurance relationships
  – Higher mean critical force (= critical force x duty cycle)
  – Proposed Acceptable levels
    ◊ If Duty Cycle = 0.5 -> 25-40% MVC
    ◊ If Duty Cycle = 0.67 -> 15-20% MVC
    ◊ Depends on duty cycle and cycle time
Intermittent Work: Definitions

Contraction Level (%MVC) vs. Time

\[ DC = \frac{W}{CT} \]

- \( W \) represents Work
- \( CT \) represents Cycle Time
- \( DC \) represents Duty Cycle

Intermittent Cyclic Work

- **Problems**
  - Difficult to establish general relationships among CL, DC, CT
  - Limited existing work, two-factor only (CL, DC)
  - Large # of potential conditions
  - Lack of evidence to support guidelines

- **Preliminary work**
  - Examine fatigue and endurance over a range of intermittent static tasks
  - Determine task acceptability (based on fatigue)
  - Develop general models
Individual Differences

- **Gender differences**
  - Most are related to underlying differences in absolute strength levels and anthropometry (e.g., body segment mass)
  - Little difference in fatigue/endurance at normalized levels, though some evidence for fatigue resistance in females

- **Age differences**
  - Decreases in endurance time with age (related to strength loss)
  - Age-related increase in fatigue resistance at normalized levels (preferential loss of Type II fibers)

Characterizing Tasks

**4 Tasks, same mean load**

![Load vs Time Graphs]

- Static
- Dynamic

**Graphs:**
- Static load: Consistent load with minimal fluctuations.
- Dynamic load: Load changes over time, with peaks and troughs.

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Ergonomics - M.A. Nussbaum
Characterizing Tasks, contd.

- Anisotonic tasks (variable exertion level)
- How to characterize (describe) such conditions?
  - Mean
  - Standard Deviation
  - Integral
- Proposed Methods
  - CPDE, CPDF: Cumulative Probability Distribution of EMG/Force
  - EVA: Exposure Variation Analysis

CPD

- Using Force, Moment, or EMG
- Percentile values characterize a task
EVA

- CPD is not sensitive to loading times
- 2 tasks, same CPDF

EVA, contd.

- Accounts for load levels and associated loading times
- 2-D Histogram
Task Characterization

• Using CPD and EVA:
  – Do parameter values change with fatigue?
    ◊ Fatigue indexes
  – Can initial task characterization predict endurance times, strength decrements, perceived discomfort, and EMG changes?
    ◊ Descriptive adequacy

• Mixed evidence (Iridiastadi et al. 2006, 2007)
  – CPD appears to have limited utility
  – EVA parameters have some ability to predict fatigue/endurance

SUMMARY

• Local fatigue is related to the effort level (%MVC)
• Subtle effects of workstations or tasks can lead to substantial changes in fatigue and endurance
• Designs that minimize joint loads, also minimize fatigue, maximize endurance, and maximize performance
• Endurance times and LMF can be used for task design and evaluation
• LMF may be an important “marker” or indicator of injury risks
• A substantial need exists for ergonomic analysis methods and guidelines for endurance and/or fatigue in realistic task conditions