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The purpose of this study was to establish the firing patterns of 15 muscles in the upper extremity and shoulder girdle of healthy female subjects during performance of the pushup. Dynamic, fine wire intramuscular electromyography was carried out in 67 healthy female volunteers. 30 women had barely passed the pushup event on the APFT within the past 6 months. 37 women had achieved a maximal or near maximal score on the APFT pushup event. 12 muscles were evaluated in all participants. 15 subjects in each group returned for testing of an additional 3 muscles. The electromyographic activity was synchronized with video. The second, third and fourth pushups in each of the narrow, middle and wide hand positions were analyzed. Differences in firing patterns between hand placements within the groups is presented. Differences in firing patterns between the minimal and maximal groups was also determined. Pre and post fatigue median frequency rates of change for each muscle were assessed. Comparisons between the minimal and maximal groups were determined. Analysis of demographic and anthropometric measurements revealed no significant differences between the groups.

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FOREWORD

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TITLE: Muscle Activity and Fatigue During Pushups Performed By Women: An Electromyographic and Videographic Analysis of 15 Muscles

KEYWORDS: ELECTROMYOGRAPHY, MUSCLE FATIGUE, FEMALE

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Introduction:

The push-up is one of three activities performed by all persons in the Army during the Army Physical Fitness Test (APFT). Standards of minimal and maximal accepted performance for the activity are profoundly different between men and women. The lower standard for and performance by women allegedly reflects the relatively smaller upper body mass and strength of women in comparison to men.

Women are particularly prone to developing overuse injuries involving the upper extremities. Jones demonstrated that during basic training, women sustain nearly double the number of musculoskeletal injuries experienced by their male counterparts (Jones 1993). It has been presumed that strength differences between men and women underlie the disproportionately high injury rates in women. A review of the existing literature suggests that leg strength in women is closer to that found in men than arm strength. On average, women are 64% as strong as men regarding upper body strength (Laubach 1976). This difference is reflected in the Army Physical Fitness Training Manual (FM 21-20). It is noted that women of equal stature to their male counterparts are globally only 80% as strong.

Over the last two decades, a significant demographic shift has occurred in the armed forces. Women made up only 1% of active duty soldiers in 1971. Currently, 11% of the military is female (Holm 1993). Over 50,000 previously prohibited assignments in the Army were recently made accessible to women. Women continue to make ever increasingly important contributions to all aspects of military preparedness.

The push-up has been utilized by the Army since the 1950's as an exercise to improve upper body strength. It is also an integral part of the APFT. The semi-annual test was designed to assess the effectiveness of training programs (FM 21-20). Additionally, performance on the APFT may have direct implications regarding retention and promotion in the Army. In accordance with AR 350-15, "the lowest passing standards reflect the minimal acceptable fitness level for all soldiers, regardless of MOS or component" (FM 21-20). Units may require minimum standards higher than the minimum APFT scores in accordance with their mission.

Women continue to be at a disadvantage relative to their male counterparts in regard to the push-up event. While women are required to perform fewer push-ups, differences between minimum and maximum standards between the sexes are more subtle. On average, women are required to perform 60% fewer push-ups than men of similar age levels to pass the event. Women's standards for maximal achievement within the same age groups on the push-up event are only 30% below the male maximum level. In an environment of increasing competitiveness among men and women for promotion and retention, assessment of the criteria upon which such career advancements are based is essential to ensure equal opportunity, while maintaining the peak efficiency of the fighting force.

Additionally, while the push-up is used intuitively to assess upper body strength, there is a paucity of information available on the actual muscle firing patterns during the push-up. Knowledge of upper extremity and particularly shoulder girdle muscle activity for this activity is important. Abnormal firing patterns and patterns of fatigue may underlie the development of soft tissue injuries. A comprehensive understanding of the muscle activity during the push-up would accurately identify the specific muscle groups at greatest risk for injury. It would enable clinicians to develop rational strengthening programs which might improve performance by women, prevent the onset of injuries, and allow for more rapid and complete rehabilitation following an injury. Analysis of the Physical Medicine and Rehabilitation outpatient clinic data base, supports the clinical presumption that soft tissue and nerve injuries involving the upper extremities are more prevalent during periods of increased activity. The development of such injuries may be temporally related to preparation and completion of the APFT.

Despite the widespread use of the push-up by both military and civilian persons to improve upper body strength and endurance, there is limited information regarding its biomechanics. A paucity of studies assessing its validity as a measure of strength and endurance have been undertaken.

A thorough review of the medical literature revealed only a single study examining electromyographic (EMG) activity of muscles during the push-up performed by women (Hinson 1969). Hinson examined 20 women, 10 of whom could execute 10 or more push-ups and 10 who could not perform five kneeling push-ups. Surface electrodes were placed over the triceps brachii, middle deltoid, anterior deltoid, pectoralis major, trapezius, serratus anterior, rectus abdominous and external oblique muscles. Hinson suggested that the greatest EMG activity was generated by the anterior deltoid muscle. EMG activity generated by muscles of unskilled women overlapped that generated by muscles in those skilled at the activity.

Several methodological flaws limit the conclusions that can be drawn from this study. The use of surface electrodes profoundly limits the ability to discern EMG activity arising from overlapping muscles (e.g., EMG signals attributed to the trapezius may in fact reflect the summation of activity occurring in the trapezius and underlying scapular retractors such as the rhomboids). Electrical activity emanating from muscle fibers travels through a volume conductor, made up of the interstitial tissues of the body before being detected by the recording electrodes. This electrical activity moves both toward and away from the electrodes. Thus, both positive and negative deflections are recorded. Typically these signals are recorded with AC coupled amplifiers, insuring that the average value will be zero. Simple averaging of the signal provides no useful information. Raw EMG signals need to be rectified and integrated to provide quantifiable measures. Additionally, noise and baseline activity, which may inadvertently add or subtract from the raw signal, was not subtracted out.

Standard measures of strength for individual muscles were also not established. This significantly limits the ability to compare activity levels between the same muscles in different individuals or different muscles in the same individual. A muscle with a large cross-sectional area may generate a large summated raw EMG signal but may only be working at a minimal capacity. A muscle with a small cross-sectional area may generate a relatively smaller summated EMG signal but be working maximally. The relative importance of individual muscle use can not be determined by the methods used.

A recent review of literature assessing the validity of the APFT as a valid measure of aerobic fitness, strength and endurance revealed only five relevant studies (Knapik 1989). Four of five studies examined only men (Fleishman 1964, Baumgartner 1972, Zuidema 1974, McCloy 1956, Larson 1941). Factor analyses suggested that the push-up is an acceptable measure of upper body strength and endurance. The single study examining women led to a similar conclusion. Major limitations in the generalizability of these findings stem from the lack of uniformity of test administration (i.e., time allowed to complete activity, criteria for correct repetition and body position.) Zuidema's study, which included women, assessed a modified version of the push-up and is not applicable to the method used during the APFT (Zuidema 1974).

The push-up is a complex activity which requires precise activation of upper body muscles. A substantial body of literature employing EMG to analyze other types of dynamic upper extremity events has been compiled (Ballantyne 1993, McCann 1992, Pink 1991, Pink 1993[a], Pink 1993[b], Scovazzo 1991, Townsend 1991). These studies provide important insights into those determinants of muscle activity which may influence the efficiency of event performance. Muscles perform two basic functions: activation and stabilization. Activation commonly employs concentric contractions to accelerate portions of the limb. Stabilization utilizes isometric or eccentric contractions and offers protection to the joints while enduring substantial forces during the transfer of energy.

Studies evaluating muscle activity during baseball pitching, golf swinging, freestyle stroke swimming and butterfly stroke swimming all suggest that three main parameters of muscular contraction influence the performance of the specific events. The timing of muscular contractions is as salient as the absolute force generated. Synchronization of muscle activity is essential to the efficient and safe transfer of energy. Ultimately, it is derived from appropriate training. It is the key factor separating elite athletes from less competitive individuals. Lack of proper muscle contraction timing has also been shown to occur in persons experiencing upper extremity pain or injury (Ballantyne 1993, Pink 1991, Pink 1993[a], Scovazzo 1991). This likely reflects the body's attempt to compensate for and protect injured areas.

The role of dynamic EMG in the assessment of complex motor activities has become more prominent in the last decade with advancements in digital signal processing and microprocessor technologies. Numerous studies have been undertaken, exploring potential methods of application, techniques and appropriate manipulation and interpretation of EMG data (De Luca 1979, Lawrence 1983, Lindström 1970, Lindström 1977[a], Lindström 1977[b]). An extensive review has been compiled by Basmajian and DeLuca, which forms the foundation for the more clinically oriented experiments (Basmajian 1985).

In the studies previously mentioned, muscle contraction timing was determined by synchronizing the event, captured on high speed film with EMG activity recorded intramuscularly in multiple muscles. Prior to recording the event, resting EMG activity was recorded. Next, a maximal isometric contraction was recorded for each muscle. EMG during two to four cycles of the event were then recorded. EMG raw data was fully rectified and integrated for quantification purposes. Noise identified on the resting recording was subtracted. The peak one second EMG signal during the maximal isometric contraction was selected as the standardizing value (i.e., equivalent to 100%). Activity of each muscle was assessed every 20 milliseconds and expressed as a percentage of the standardized value. EMG activity for all muscles was synchronized with the film to obtain percent muscle activity values at interval phases of the event. By using this method, several important results can be obtained. The pattern of muscle firing can be determined throughout the entire event. The predominance of specific muscles during specific phases of the event can also be elucidated. Conversely, the phases in which specific muscles act maximally is additionally established. Conclusions regarding the importance of firing patterns and absolute muscle strength may then be derived when the performances of elite and untrained participants are compared.

Strength and endurance are the other two variables which impact on performance. Studies examining the relationship between absolute strength and absolute endurance have revealed strong positive correlations (Barnes 1980, Eckert 1967). Thus, a stronger individual is likely to have greater endurance than a weaker person. An absolute improvement in strength however, does not correlate with an improvement in relative endurance (Carlson 1971). According to Knapik, absolute strength is of greater importance in the military environment (Knapik 1989). Activities such as lifting and moving heavy machinery require short bursts of maximal strength. The strength measures on the APFT are also administered over a short period of time (2 minutes) and focus on the ability to perform maximally during that limited time-frame (FM 21-20).

A corollary to the concept of muscular endurance is fatigue. Fatigue has been defined as the onset of the inability to maintain a desired force output (Basmajian 1985). It can be difficult to measure "true" fatigue because of its complex physiological and psychological nature. Measures of fatigue which rely on the ability of persons to produce maximal work output may be confounded by psychological variables including motivation, concentration and potential secondary gains (de Lateur 1992). Definite physiologic markers of fatigue have been documented. Maximum aerobic capacity can be measured in terms of the rate of oxygen consumption (VO_2). Physiochemical markers, including a drop in serum pH and increases in metabolic by-products such as CO_2 and lactate, are also well reported.

Alteration in EMG activity is a unique indicator of localized muscular fatigue and has been extensively studied (Bouissou 1989, De Luca 1979, Kranz 1985, Lawrence 1983, Lindström 1970, Lindström 1977[a], Lindström 1977[b], Moritani 1986). It has been observed that the frequency components of surface and intramuscular EMG signals decrease as the muscle fatigues. EMG signals are formed by summation of the wave forms generated by individual motor unit action potentials. The amplitudes of these wave forms vary over time. Certain portions of the wave form change rapidly and are made up of high frequency components. Other portions change more slowly and are made up of low frequency components. The frequency composition of the wave form can be resolved using the fast fourier transform (Shochina 1986). Information regarding the amplitude, frequency and phases of the wave form during a specific time period are obtained. Because amplitudes can vary greatly, signal power in decibels rather than amplitude is usually expressed. The relationship of power levels and frequency domains can then be plotted. Dynamic frequency analysis is the assessment of power spectra at regular intervals over a period of time. Stulen and DeLuca performed mathematical analyses which suggest that the median frequency and mean frequency of the power spectra are the most reliable parameters used to represent the spectrum (Stulen 1981). The median frequency is the frequency at which the power density spectrum is divided into two regions of equal power. The mean frequency is the average frequency. Of the two, the median frequency is less sensitive to extraneous electrical activity which may be seen at the extreme ends of the distribution and is also less affected by the skew of the spectrum. A strong correlation between the rate of change in the median frequency and muscle fatigue has been documented. In one study examining the endurance of muscles in the low back, a correlation coefficient of $r = 0.69$ was attained (Mannion 1994).

The proposed study will provide important insights into methods now commonly employed by the Army to improve upper body fitness. It will be conclusively determined as to which muscles are utilized during the push-up and the firing patterns used by elite and unskilled individuals. The proposed study will also determine which muscles are at greatest risk for fatigue and potential injury.

From this data, rational programs may be devised which may improve the upper body strength and performance of female soldiers. The development of training paradigms based on the activity of elite athletes is the state-of-the-art method utilized by sportsmedicine practioners to enhance performance of skilled individuals and improve the caliber of performance of less proficient individuals. The information derived from this study may also lay the groundwork for preventative programs that may limit the development of upper body musculoskeletal injuries.

Body:

Healthy military women volunteers from active duty or reserve components, aged 18 to 51, were recruited from the troop populations in the National Capital Area. Two groups of women were studied. One group, termed "elite", was composed of women who achieve or exceed a maximum score in the push-up event of the APFT standards for a maximal score based upon their age group or who score above 90 points according to APFT push-up scoring. 37 women meeting standards for this group were tested. The second group, termed "unskilled", was composed of women who either do not achieve the minimal passing score on the APFT push-up event or score below 71 points according to APFT pushup scoring. 7 subjects of the 67 tested will not be used in statistical analyses due to electromyographic recording problems during their testing.

Informed consent was rendered. Demographic information was obtained. Height, weight, arm length and shoulder span were measured. Dynamic electromyographic recordings were made using disposable 44gauge paired hooked wires were inserted into 12 muscles in the upper extremity, shoulder girdle and abdomen. Each subject performed 15 second isometric contractions of each muscle. Next each subject performed 3 sets of pushups. Each set was 5 repetitions with hand placed in different positions for each set. Next, one set of pushups was performed to fatigue. Lastly, a second set of 15 second isometric contractions was performed. Synchronized electromyographic and video information was collected during the isometric contractions and during the 3 sets of pushups. 30 subjects are to undergo the same protocol on 3 additional rotator cuff muscles.

Raw EMG signal was recorded. To allow for quantification, the signal was full wave rectified, which requires inversion of all negative values. The signal was then averaged to smooth the rectified signal. The second and fourth push-up of each set were divided into 20 equal segments. The area under the curve will be calculated and expressed in μV^*s for each segment. EMG activity in each muscle was collected during the initial isometric contractions. The average area over the maximal 1 second period for the comparable time segment during the push up was calculated to establish a standardizing value. The area under each segment will be reported as the percentage of the standard value for each muscle.

Analysis of the collected data is currently underway. Determination of which muscles are used predominantly during the push-up event will be determined. Differences in patterns of muscle use between elite and unskilled groups will be determined. The firing patterns and utilization of muscles during different periods of the push-up and the influence of hand position will also be determined.

Dynamic spectral analyses will be used to evaluate fatigue patterns. Only muscles attaining activity levels in the **marked** range, during any point in the event will be assessed. It is presumed that these muscles are the prime movers of that motion. The rate of fatigue, as determined by the slope (rate of change) of the dynamic median frequency for individual muscles will be determined. Comparison will be made between the pre-push-up 15 second isometric tests and the post-pushup to fatigue, 15 second isometric tests. Determinations regarding muscle most susceptible to fatigue (i.e., the muscle(s) which likely prevent continuation of the event when they fatigue) and differences in fatigue between groups and between hand placements will be made.

An analysis of demographic and anthropometric data will also be performed.

Conclusions:

Due to the interim nature of the study, no conclusions can be made at this time.

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