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BIOMECHANICAL EFFECTS OF LOADED MARCHING AND RESULTING TRAINING RECOMMENDATIONS

Loaded marching (rucking) is a critical component of military members conducting combat operations (2). Dismounted mobility, defined as the capability of a soldier to traverse through any kind of terrain irrespective of weather conditions, is often the only means of maneuvering to an objective if vehicle infiltration is infeasible or vehicle pickup and dropoff locations are used to maintain surprise (17,22). Army Training Publication 3-21.8, *Infantry Platoon and Squad* describes the characteristics of offensive operations as tempo, surprise, concentration, and audacity (1). To do this effectively, military personnel must move quickly over harsh terrain to maintain operational tempo and achieve surprise, carry all required combat equipment to mass the effects on target, and maintain a level of cognitive awareness to seize and maintain the initiative. Enabling military professionals to succeed in this environment requires an understanding of the biomechanics of loaded marching over terrain.

Military personnel are often required to carry gear, including ruck, weapon, and personal protective equipment exceeding 45% of their bodyweight in various environmental conditions (24). The impact on gait biomechanics often results in additional fatigue and injury risk which may detrimentally impact their ability to accomplish operational objectives (17). As the body means to move as efficiently as possible, it will adapt gait changes to ultimately 1) control the external load as much as possible and to 2) minimize the energy cost associated with carrying the load (6).

The addition of a weighted ruck sack will shift the center of mass (COM) posteriorly and superiorly relative to the body, and the more weight that is carried, the greater this shift will be. To manage this, the body will adopt strategies to maintain both the external load and the body's center of mass over the base of support. This is achieved primarily via a forward trunk lean. As ruck load increases, the angle of trunk lean may increase. Additionally, at certain thresholds of pack load relative to body weight, the neck and head may also be recruited for additional counterweight whereby the head is placed farther forward. These strategies result in increased demand on the spinal extensors muscles which may increase risk for strains of the low back and neck (5,6).

Step length is another variable that may change under load. Most research indicates that when walking speed is held constant, most people respond to load bearing gear by 1) decreasing their step length and/or 2) increasing step rate (6). It is important, however, to note that research is inconsistent with this finding in that sometimes it has been seen that individuals instead maintain walking speed by conversely increasing step length and decreasing step rate. To explain this inconsistency, it has been hypothesized that professionally trained individuals will respond with the aforementioned step length decrease while untrained individuals will respond with a step length increase, but this may also be influenced by leg length and other morphological differences (5). Each strategy will have different biomechanical advantages and injury considerations.

Ground Reaction Force (GRF) describes the interaction between the individual and the ground during movement and is another variable that is affected by load carriage (7). To describe GRF, it is important to consider three GRF components: vertical GRF, anterior/posterior GRF, and mediolateral GRF. In unloaded walking, vertical GRF is the largest component with peaks registering at approximately 1.2 times/body weight and increases in walking speed promoting increases in GRF (7). The addition of load bearing gear has been shown to increase vertical GRF by approximately 10N for every 1 kg of external load added (6). Although the effect is less than with vertical GRF, anterior/posterior GRF are also affected by external load. Additionally, anterior/posterior GRF will be more affected by cadence changes with slower cadence associated with greater GRF (6). This ties back to earlier discussions regarding step length and step rate adjustment strategies.

Lastly, mediolateral GRF is the least affected by external load but still worth discussing especially when the load carrier may find themselves navigating overland terrain. Research has indicated that mediolateral GRFs increase as load carriage weight increases likely due to decreased stability and increased sway (5). This will become more pronounced on uneven terrain and will require training considerations to ensure that medial/lateral postural stabilizers are adequately trained. These training considerations will be discussed later in this article.

While the aforementioned biomechanical changes are adaptations to increase efficiency to manage the stress of the external load, there are important injury trend considerations that can happen as a result. As previously mentioned, increased forward trunk lean and head posture results in increased muscular demands of the cervical and lumbar paraspinals and then abdominal muscles which in turn can cause strains of the neck and back. Another effect of the increased forward trunk lean is that of increased angle of hip flexion relative to the trunk, which may increase demands through the hip joint and hip flexor muscle group. All of this then becomes magnified if navigating elevation gain and uphill climbs on overland and possibly uneven terrain.

As previously highlighted, GRF will increase with the addition of external load. First and foremost, this causes concern for the risk of bone stress injury (BSI) of the lower extremities as we increase demands on the skeletal system. BSI is an overuse injury that can occur when a bone is subjected to repeated stress causing microdamage which then exceeds the rate at which the body can remodel and form new bone. As the body fails to continue the required rate for bone remodeling due to sustained loading or inadequate rest periods, micro-fractures can develop. Common BSI sites in military recruits include the metatarsals, tibia, and femur. While there are additional modifiable risk factors increasing risk of BSI such as high body fat, use of certain medications, alcohol, and nicotine, and inadequate nutritional intake, this article will focus on the training priorities and program progressions that are recommended to decrease risk of injury (7).

Additionally, the effect of increased braking mechanism as the load carrier attempts to reduce momentum from the external load must be considered (5). These considerations become even greater if we need to account for increased momentum associated with navigating downhill terrain. Braking mechanism and deceleration moments are characterized by rapid flexion of the hip, knee and ankle. This energy is then dissipated by eccentric muscle work and tendon loading. It has been found that high cumulative deceleration loading over a 2 – 4 week period leads to an increased risk of overuse injury. This is likely best explained as an imbalance in the load capacity and remodeling rate of the tissue versus the rate, duration, and intensity of the deceleration loading. Training considerations to improve eccentric strength capacity and avoid spikes in training volume should be given to help mitigate this injury risk (15).

To mitigate injury risk and improve loaded march performance, practitioners may consider using a concurrent total body resistance training and aerobic training approach. Kraemer et al. suggested that concurrent resistance and aerobic training showed the most significant improvement in a two-mile loaded run with a 44.7-kg ruck, compared to resistance training only or endurance training only in male soldiers (13). Given the aforementioned biomechanical analysis of loaded marching, a total body resistance training approach directly addresses the need to improve trunk and erector spinae musculature, along with eccentric quadricep strength and overall lower body strength and power.

Concurrent total body resistance and endurance training is a strong mitigating factor for potential BSI when workload is managed appropriately (25). It is well established in research literature that exposing bones to mechanical load that exceeds daily activities has an osteogenic effect (9). The challenge faced by practitioners in a concurrent resistance and aerobic training program is managing the training load. As important as it is to expose bone to increased mechanical loading, it is also necessary to manage the workload to avoid spikes in volume that increase risk of BSI. While some general rules or mitigation measures have been established (such as the “10% rule” or acute:chronic workload ratio), it is better to individualize workload progression due to the complex interaction between biomechanics, physiology, psychology, musculoskeletal qualities, and energy availability (25).

Strength and conditioning professionals should also recognize that service members are required to carry a ruck not only during formal fitness assessments—typically performed on roads or other stable surfaces—but also across variable and uneven terrain during tactical movement and maneuver tasks. As surface instability and grade change, mediolateral GRF and the associated postural demands become increasingly pronounced. These demands are further magnified by the addition of distally carried or elevated loads such as weapons systems, helmets, and upper-body mounted equipment. Because these loads increase the moment arm relative to the COM, even small increases in distal weight can create disproportionately large changes in trunk lean, lateral sway, and overall gait mechanics. This results in greater reliance on the lateral stabilizers of the hip and trunk and can compound fatigue during prolonged load carriage.

To mitigate these postural and biomechanical challenges and improve load-carriage efficiency, targeted strengthening of the lateral stabilizers (e.g., hip abductors and quadratus lumborum) should be incorporated. This can be effectively achieved through unilateral carry variations and lower-body movements such as squats, step-ups, and lunges, supplemented by frontal-plane exercises (e.g., lateral step-ups and lateral lunge variations).

In addition to targeted strength development, service members should undergo progressive acclimatization to the specific loads and equipment they are required to carry. Gradual exposure to operational loads allows the neuromuscular system to adapt to altered COM positioning, increased moment arms from distal equipment, and changes in trunk and pelvic mechanics. Load acclimatization has been shown to improve gait economy, reduce excessive trunk lean and mediolateral sway, and enhance tissue tolerance by distributing stress more effectively across the kinetic chain. Incorporating structured progressions in load, duration, and terrain complexity ensures that adaptations occur safely while minimizing the risk of overuse injury.

While traditional strength and conditioning can directly address many of the biomechanical effects of loaded marching, it is helpful to also consider that exposure to the terrain itself is a training variable that can be progressed. One study measuring variability of step length, step width, and COM during repeated exposure to uneven terrain found that as familiarity increased, step length increased and variability of anterior-posterior COM and step length reduced (10). This suggests that more time in the terrain itself will improve locomotor function and overall postural control. With this in mind, the strength and conditioning professional may consider gradually increasing the time or frequency that the service member spends in the environment to develop the locomotor skills to move efficiently over terrain.

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SUMMARY OF STRENGTH AND CONDITIONING RECOMMENDATIONS

To optimize performance in loaded marching and mitigate injury risk, strength and conditioning programs should emphasize a combined approach integrating resistance training, aerobic conditioning, and terrain exposure.

1. CONCURRENT TRAINING APPROACH

Evidence indicates that concurrent resistance and endurance training yields superior improvements in load-carriage performance compared to resistance or endurance training alone. Kraemer et al. demonstrated that soldiers performing both modalities showed the greatest improvements in a 2-mile loaded run compared to single-modality groups (13). More recent reviews confirm that pairing progressive resistance training with aerobic conditioning, approximately three times per week, enhances resilience and reduces overuse injuries during load carriage (18,20).

2. LOAD-CARRIAGE SPECIFIC TRAINING FREQUENCY

Narrative reviews recommend including load-carriage sessions every 7–14 days, using progression strategies that manipulate load weight, terrain, and speed rather than simply increasing distance (20). Research from Orr et al. highlights that this frequency provides sufficient stimulus while allowing adequate recovery, and reducing musculoskeletal injury risk during repeated rucking demands (18).

3. LOWER-BODY STRENGTH AND POWER

Lower-body strength and power are key predictors of load-carriage performance. A systematic review and meta-analysis found significant correlations between squat strength, vertical jump performance, and marching capacity under load (19). Accordingly, programming should emphasize posterior chain development (deadlifts, hip hinge variations) and eccentric quadriceps strength (split squats, step-downs) to manage braking forces, particularly on descents.

4. TRUNK AND POSTURAL CONTROL

The biomechanics of rucking place increased demand on spinal extensors, abdominals, and hip flexors. Strengthening these tissues through trunk stability training (loaded carries, anti-extension core work, and posterior chain exercises) is essential. Emerging evidence suggests that upper-body strength (e.g., pull-ups, bench press) is also strongly correlated with load-carriage performance, likely due to its role in maintaining posture under load (16,20).

5. BONE STRESS INJURY MITIGATION

Bone health benefits from mechanical loading that exceeds daily activity, but progression must be carefully managed. Overuse injuries such as medial tibial stress syndrome and stress fractures are often associated with rapid spikes in training volume. Research supports gradual workload progression and individualized programming to mitigate these risks (8,18).

6. AEROBIC CONDITIONING AND FATIGUE MANAGEMENT

Aerobic fitness supports operational tempo by improving movement economy and delaying fatigue. Studies suggest managing pace and external load to maintain exercise intensity near 45 – 47% of VO_2max can prolong endurance under load (4). Steady-state sessions and intervals should both be integrated into the program to prepare soldiers for sustained marches and rapid maneuvering.

7. TERRAIN EXPOSURE AS TRAINING

Locomotor variability decreases with repeated exposure to uneven terrain, leading to improvements in step length, center of mass stability, and overall efficiency (10,23). Accordingly, programs should gradually increase training time in terrain environments to complement gym-based strength and conditioning interventions.

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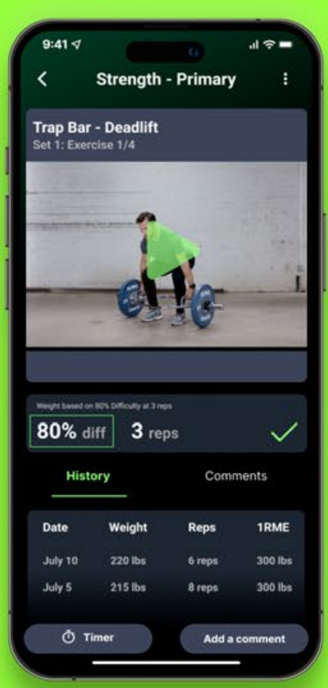

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