Preventing Injuries Associated with Military Static-line Parachuting Landings

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Abstract Military static-line parachuting is a highly tactical and hazardous activity, with a well-documented injury risk. Due to the high impact forces and rapid rate of loading when a parachutist lands, injuries most frequently occur to the lower limbs and the trunk/spine, with ankle injuries accounting for between 30 and 60 % of all parachuting injuries. Although military static-line parachuting injuries can be sustained at any time between the paratrooper attempting to leave the aircraft until they have landed and removed their harness, most injuries occur on landing. Throughout the world, various landing techniques are taught to paratroopers to reduce the risk of injury, by enabling parachute landing forces to be more evenly distributed over the body. In this chapter, we review research associated with static-line military parachuting injuries, focusing on injuries that occur during high-impact landings. We summarize literature pertaining to strategies for military paratroopers to land safely upon ground contact, especially when performing the parachute fall landing technique. Recommendations for future research in this field are provided, particularly in relation to the parachute fall landing technique and training methods. Ultimately, any changes to current practice in landing technique, how it is taught, and whether protective equipment is introduced, should be monitored in well controlled, prospective studies, with the statistical design accounting for the interaction between the variables, to determine the effect of these factors on injury rates and paratrooper performance. This will ensure that evidence-based guidelines can be developed, particularly in relation to landing technique and how this is trained, in order to minimize injuries associated with landings during military static-line parachuting in subsequent training and tactical operations.

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1 Introduction

The act of parachuting involves descending through the air using apparatus to increase air resistance, thereby reducing the velocity of motion [1]. Parachuting is performed for many reasons, but chief among these are occupational and recreational pursuits. Although recreational enthusiasts constitute hundreds of thousands of the world's parachuting populace [2], most participants come from occupational groups including firefighters (known as smoke jumpers) and rescue groups [3], with the vast majority being military paratroopers [4]. One of the main purposes of military parachuting is to rapidly deliver a large contingent of armed personnel onto a battlefield, in a manner that enables the soldiers to arrive safely on the ground and ready to immediately commence operational missions [3, 5, 6]. Military parachuting was initially used during World War I by the US army as a strategy for "vertical battle engagement", which allowed for the capture of strategic objectives at the rear of an enemy [7]. Since that time, use of military parachuting has become standard practice in armies around the world to deploy combat forces.

During military operations, troops are usually deployed at low altitudes using static-line parachuting, whereby the parachutist hooks his or her parachute onto a 'static' line, which is firmly attached to a strong point on the aircraft [8, 9]. Upon exiting the aircraft, this line is designed to pull the parachute canopy and rigging free from its bag until it is fully opened [9]. In contrast, free fall parachutists, also known as skydivers, are responsible for deploying their own parachute. Although some military personnel also perform free fall jumps, static-line parachuting is the primary airborne means for mass troop deployments [8]. Due to the highly tactical nature of static-line parachuting and the type of equipment used, this form of aerial descent is generally acknowledged as the most hazardous [4, 10, 11].

Although parachuting comes with an inherently high level of injury risk, keeping injuries to a minimum is essential to the readiness, effectiveness, morale, and efficient running of any military unit [12, 13]. In an operational environment, paratroopers who sustain a severe injury are likely to be unable to continue their mission and, therefore, require both medical and evacuation resources for their management [6]. In fact, an injured paratrooper may require up to four soldiers to assist in evacuation from a drop zone [14]. This imposes a substantial operational and logistical burden for commanders [6]. Furthermore, parachuting injuries can occur in both tactical and non-tactical scenarios, with the more severe injuries potentially affecting a soldier's long-term health [13]. In fact, when parachuting goes wrong, the potential for a career-threatening or life-threatening injury is great [15]. As parachuting injuries can have a serious negative effect on the physical health of paratroopers, and in turn the combat capability of the military, analyzing factors that affect parachuting injuries is of military significance [16].

It is well recognized that landing is the most dangerous part of parachuting. That is, most military parachuting injuries occur during impact with the ground when parachutists are forced to absorb extremely high impact loads [9, 16–18]. For this reason, it is imperative that military paratroopers learn to instinctively employ a safe landing technique to effectively absorb these high impact forces, irrespective of potential distractions during the descent, such as gusting winds, uneven terrain or loose equipment [17]. In this chapter, we review research associated with static-line military parachuting injuries, focusing on injuries that occur during high-impact landings. We summarize literature pertaining to strategies for military paratroopers to land safely upon ground contact, particularly when performing the parachute fall landing technique. Recommendations for future research in this field are provided, so that evidence-based guidelines can be developed, particularly in relation to landing technique and how this is trained, in order to minimize injuries associated with landings during military static-line parachuting in subsequent training and tactical operations.

2 Military Parachuting

As stated above, one of the primary requirements of military parachuting is to enable soldiers to jump from an aircraft and land safely on the ground, ready to immediately undertake their combat duties [9]. Unlike their recreational sky diving counterparts, military paratroopers are likely to parachute in a hostile environment, which creates unique demands on how military parachuting is performed. For example, in order to avoid radar and anti-aircraft weapons systems, military aircraft fly as low as possible, usually below 2000 feet above ground level, to minimize exposure [19]. Soldiers also attempt to exit the aircraft as fast as possible to minimize the time the aircraft spends over the drop zone and to minimize troop dispersion [7, 9]. Although some special operations forces use military free fall, including tactical high altitude-low opening (HALO) airborne operations [19], the primary means of parachuting for mass troop deployment is static-line parachuting [8].

Despite substantial changes in modern warfare, principles underlying static-line military parachuting have remained relatively unchanged since the 1940s [9]. A soldier typically carries their military parachute in a bag on his or her back, with a reserve parachute attached to the front. On command from a “jumpmaster”, each soldier stands up and hooks a cable from their individual parachute to a static line, which is attached to a strong point inside the aircraft and runs the length of the aircraft [3]. When the doors are opened, each soldier shuffles to an aircraft door and, on command, exits from the aircraft in quick succession [9]. As the soldiers descend, the static line pulls the parachute and rigging lines from each soldier’s bag until the breaking strain of the tie holding the static line to the parachute is exceeded. At this point, the static line breaks off and each soldier drifts to the ground (see Fig. 1).

The parachute used in military static-line parachuting is typically a round non-steerable canopy. Although the parachute can be maneuvered a little by pulling on the risers (cords that connect a soldier’s harness to the actual parachute) and

Fig. 1 Paratrooper drifting to the ground after a static-line parachuting exit

allowing some air to spill out [9], the jumper has little control over their vertical velocity or direction on landing [19]. If a soldier is required to carry military equipment, the equipment is usually attached below the reserve parachute and can be lowered on the end of a rope while they are descending so that the soldier is unencumbered upon landing [9]. When the parachutist contacts the ground, he or she uses a well-rehearsed landing technique in an attempt to dissipate the high impact forces that are generated at ground contact (see Sect. 5). The soldier then removes the parachute as quickly as possible so they can be ready for ground operations [3].

Despite parachuting being a relatively efficient method of deploying troops, there have been substantial injuries associated with military static-line parachuting [8]. This is not surprising, given the fast descent velocities and, therefore, high impact forces and rapid loading rates encountered when a paratrooper lands from this hazardous form of aerial descent [20]. As these injuries can have substantial negative consequences on the physical and emotional health of parachutists, as well as impact the combat capabilities of an entire military unit, it is imperative that mechanisms of parachuting injuries are understood in order to develop evidence-based strategies to minimize their occurrence.

3 Static-line Military Parachuting Injuries

3.1 Parachuting Injury Risk

In the 1930s, injury rates recorded for military parachuting were as high as 680 per 1000 jumps [12] while during World War II (January–November, 1944) an injury incidence of 21 per 1000 jumps has been reported based on 20,777 jumps undertaken by trained parachutists [21]. However, with major improvements in parachute design and technology, aircraft exit procedures, landing techniques and training, in combination with a better practical understanding of the risk factors involved, these rates have substantially declined to an average of approximately 6–11 per 1000 jumps [3, 5, 9, 22].

When interpreting injuries rates, it is important to remember that military parachuting involves a wide variety of activities, varying from controlled training jumps over flat terrain in daylight to highly tactical jumps under combat conditions over unknown terrain at night [18]. The injury rates during training courses are, of course, much lower than those reported during airborne operations or actual combat. For example, in a study of 59,932 static-line parachute descents performed by Chinese People's Liberation Army cadet pilots during basic training, the overall injury incidence was 2.6/1000 jumps [15]. In contrast, the total injury incidence during a combined United States (US) and United Kingdom (UK) parachuting mass tactical operation, involving combat equipment conducted at night during inclement weather, was 28.8 injuries per 1000 aircraft exits with 24.6 injured soldiers per 1000 aircraft exits (from a total of 4754 aircraft exists; [13]). A comprehensive table of injury rates for military parachuting (injuries per thousand descents) between 1941 until 1998 is provided by Bricknell and Craig [9]. A relatively recent tabulation of the injury incidence in military parachuting, including events associated with injury, and a quantitative assessment of injury risk factors and their interactions during military parachuting is provided by Knapik et al. [5]. It is acknowledged that between-study variations in injury incidences are frequent. These variations can be attributed to differences in injury definitions and study design, how the data were collected, as well as variability between parachute schools, jump conditions, national affiliations of the soldiers, training experience, whether the data were collected during training or operations, and risk factors present during jumps [2, 3, 5]. For example, injury definitions can vary from any medical treatment administered on a drop zone, no matter how minor, to only major casualties receiving attention at hospitals [3, 9]. Furthermore, it is speculated that the frequency of minor parachuting injuries may be underestimated in many military studies, particularly in retrospective studies, because of the desire of military personnel to complete a parachute-training course, and their consequent reluctance to report injuries for fear of medical disqualification [19, 23, 24].

3.2 Parachuting Injury Characteristics

Irrespective of between-study differences in injury incidence, research shows a common trend in terms of the type of injury incurred during military static-line parachuting [9]. That is, injuries to the lower limbs [8, 13, 15] and the trunk and spine are the most prevalent [7, 23, 25]. In fact, lower limb injuries have been reported to be as high as 70–80 % of the total parachuting injuries incurred [7, 15, 18]. Ankle injuries, particularly ankle sprains and fractures, are largely responsible for this latter statistic, accounting for between 30 and 60 % of all parachuting injuries [15, 23, 24, 26, 27]. The high incidence of lower limb and trunk/spine injuries is not surprising, given that these injuries are typically associated with the high impact forces generated at ground contact during a parachute landing [3] and the rapid rate of loading sustained when a paratrooper lands [28], with the lower extremities taking the initial impact of a parachutist's full body weight [7, 17].

A notable exception to most injury profiles was a study of 23,031 jumps taken by members of an airborne infantry unit [5]. In this study the most common injury/anatomical location combination was closed head injuries/concussions (30.6 %), although ankle fractures and ankle sprains were the second most frequently occurring injury (16.9 %). Closed head injuries are of concern as they reflect the vulnerability of the brain to impact [9]. Interestingly, the injury rate for severe injuries during parachuting is relatively low for military operations. For example, Ekeland [18] reported that the risk for fracture or knee ligament rupture was only 2.0 per 1000 jumps during basic courses for paratroopers and 1.2 per 1000 jumps during training exercises. The overall risk of incurring a severe injury in their prospective study was 1.6 injuries per 1000 jumps [18]. More recently, Guo et al. [15] reported a similar low rate of 1.2 per 1000 jumps for severe injuries, whereby fractures, dislocations and ligament ruptures were classified as severe injuries. As such, military static-line parachuting is considered a relatively safe method of troop transportation [18], although it is acknowledged that the consequences of severe injuries can be catastrophic.

Military static-line parachuting injuries can be sustained at any time between the paratrooper attempting to leave the aircraft until they have landed and removed their harness. Injuries typically occur during one of four main phases during the sequence of a parachute jump: (i) when exiting from the aircraft, (ii) during opening of the parachute, (iii) during the descent, and (iv) on landing [16]. Most injuries, however, occur on landing [17]. For example, in an analysis of 23,031 jumps performed by an Army airborne infantry unit, with an injury incidence of 10.5 per 1000 jumps [5], 75 % of those injuries in which an event associated with the injury could be determined involved problems associated with ground impact. Static line problems (11 %), tree landings (4 %), entanglements (4 %), and aircraft exits (3 %) accounted for most of the other injuries [5]. Other studies have reported that 85–90 % of all parachuting injuries occurred during the landing [8, 16, 18], supporting the belief that landing is considered the most dangerous phase of a parachute jump. Given that most military static-line injuries are associated with ground contact, the remainder of this review will focus on injuries occurring during this phase of the parachuting movement. A comprehensive overview of the mechanisms of parachuting injuries occurring before landing is provided by Bricknell and Craig [9].

3.3 Risk Factors for Military Static-line Parachuting Injuries

Despite wide variations amongst studies investigating military static-line parachuting injuries, the data are relatively consistent with respect to whether or not a particular factor increases the likelihood of incurring an injury [3]. For example, studies have consistently shown that the risk of injury increases when parachuting is conducted while there are higher wind speeds [9] and higher dry bulb temperatures, during night jumps compared to day jumps, jumping with combat or heavy loads compared to unloaded jumps, jumps without wearing ankle braces, jumping onto uneven or rough terrain where obstacles are present (e.g. trees, rocks, fences and power lines), and when there have been entanglements [3, 5, 23]. Purpose built sand drop zones used by the US military for paratrooper training have been shown to reduce the injury rate 3.2 fold [3]. Numerous other factors that have been implicated in affecting the risk of sustaining a military parachuting injury are aircraft and parachute type-specific (i.e. model of aircraft, location of exit doors, number and sequencing of soldiers exiting the aircraft, and parachute canopy size and shape; [3, 5]) or factors that reduce ground visibility during descent like low cloud cover [13]. Knapik et al. [3] has provided a comprehensive review of studies examining risk factors for injuries during military parachuting. Some of these risk factors can be controlled during training (e.g. imposing wind speed limits on training jump days). Others (e.g. night descents, multiple parachutists leaving the aircraft and the carriage of equipment), however, are fundamental to the operational capabilities of parachute forces and, therefore, cannot be avoided during military operations (see Table 1).

Table 1 Factors associated with military parachuting injuries

Factor	Effect on injury rate
Wind speed	Increasing wind speeds increase rate
Multiple parachutists leaving aircraft	Increase
Night descent	Increase
Carriage of equipment	Increase
Nature of dropping zone	Hard, uneven or hazards increase rate
Balloon descents	Decreased relative to aircraft descents
Design of parachute	Decreased with modern parachutes
Height and weight of parachutist	Increase
Inexperience of parachutist	Increase

Adapted from Bricknell and Craig [9]

Although intrinsic injury risk factors have also been explored, there tends to be less consistency with respect to which variables are associated with an increased injury risk. Higher injury risk, however, has been associated with intrinsic risk factors such as greater body weight, older age and/or longer time in service ([29–32], less upper body muscular endurance, lower aerobic fitness, and prior injuries [22]; taller stature, fewer push-ups, and slower 2-min run times [31]. Jaffrey and Steele [23] noted that 25 % of Basic Parachute Course trainees with the slowest 2.4 km run times (>10:00 min) incurred 47 % of injuries. The authors cautioned, however, that the interaction between injury, 2.4 km run time and other parameters such as body mass requires investigation, given that parachuting does not demand high aerobic fitness and that better run times are usually achieved by lighter individuals [23].

In an investigation of parachuting injuries sustained by Chinese Air Force Cadet Pilots, the intrinsic risk factors associated with reduced injury rates were excellent mental qualities and parachuting technique, and being a female cadet pilot [16]. In contrast, Knapik et al. [3] stated that, compared with men, women appeared to be at greater risk for injuries overall and, more specifically, to have more fractures, with more injuries caused by improper landing technique. There are, however, many confounding factors when making gender comparisons in military parachuting injury rates (as discussed by Knapik et al. [3] and Guo et al. [15]), such that these comparisons should be interpreted with caution.

4 The Importance of Landing

It is well documented that, by far, most military static-line parachuting injuries occur during landing (see Sect. 3.2). For example, in an analysis of injuries sustained during a series of 51,828 military training parachute descents single injuries were the result of a hard or awkward landing on 95 out of 104 (91 %) occasions [24]. Essex-Lopresti [21] remarked, "that the euphoria accompanying the glorious sense of isolation whilst floating down is tempered by anticipation of the technical difficulties of meeting the ground" (p. 3). Landing is therefore considered the most dangerous phase of parachuting, a time when the parachutist's body is subject to the interaction of gravitational forces in the vertical plane and natural forces of wind in the horizontal plane [19]. The hazards associated with any high impact landing are increased during parachuting by factors such as poor drop zone conditions and obstacles such as trees, fences, and power lines [19]. The single largest cause of these lower limb and trunk/spine injuries at landing, however, is poor landing technique [20] (Fig. 2).

Because most parachuting injuries occur on landing it is pivotal in avoiding injuries that parachutists learn to use a proper landing technique [8]. Training has to ensure that parachutists automatically use this technique irrespective of distractions occurring during the descent, such as gusting winds, uneven or rough terrain, loose equipment or any improper function of the parachute [17, 18]. The increased injury

Fig. 2 Military static-line parachuting trainee landing on the drop zone, with medical treatment facilities available in case of injury, which is usually caused by poor landing technique

risk associated with military static-line parachuting has led to the continuous study and development of military jumping techniques so that parachutists can absorb the high impact forces generated at ground contact [7].

4.1 Impact Absorption During Landing

When a parachutist makes contact with the ground he or she is subjected to a combination of forces including the downward gravitational force, lateral forces from both wind and from oscillation and, possibly, a rotational force if the parachutist is spinning, although this is rare [9]. The lateral force caused by wind is a crucial factor that determines injury rate, as the horizontal speed component caused by wind can dramatically increase the resultant velocity with which a paratrooper impacts the ground [6]. Consequently, although steering capacity is limited (see Sect. 2), parachutists are trained to steer into the wind during the last phase of a descent in order to reduce their lateral velocity to a minimum [9].

Not surprisingly, despite variations and unpredictability in lateral and rotational forces, the primary ground reaction force generated at ground contact is in the vertical direction. It is affected by parachute design and load, including the weight of the parachutist, as well as the equipment carried during the descent [9], which may be up to an additional 45 kg [33]. Irrespective of the relative loads from the paratrooper or their equipment, vertical descent velocity under standard static-line parachutes used by the Australian and US military, for instance, may increase to as much as 6.7 m s^{-1} when the total load approaches the upper load limit of these parachutes (approximately 163 kg; [23]). The overall load (weight) of the paratrooper and their equipment affects the shape of the canopy and, in turn, the air resistance of the parachute. Basic physical principles then dictate that a system with a relatively large mass (paratrooper dressed in military fatigues and carrying equipment) and a vertical descent velocity of at least 4.6 m s^{-1}, but more likely closer to 6 m s^{-1} [17], will have a substantial amount of downward momentum at the moment of ground contact. This substantial downward momentum will, in turn, result in a relatively large impact energy that must be absorbed by the body during the landing [5]. It is beyond the scope of this chapter to discuss military parachute design in further detail, suffice to say that changes in the shape, size and materials used to construct military parachutes have been associated with a reduction in parachuting injuries (see Bricknell and Craig [9] for more details).

Irrespective of parachute design, it has been estimated that the impact forces from military static-line parachute landings are equivalent to those sustained by jumping from a 2.7–3.6 m (9–12 foot) high wall [3, 9]. By applying basic physical principles to a scenario where a parachutist must completely arrest a large amount of downward momentum in a short period of time, it is evident why these impact forces are high. A laboratory-based investigation of simulated parachute landings at three different vertical descent velocities revealed that trained military paratroopers took, on average, only 70–90 ms to reach maximum knee flexion after contacting the ground during the initial energy absorption phase of landing [20]. It is important to note that the peak resultant ground reaction force absorbed during the rapid change in momentum experienced during these landings occurred in less than half of this time [20]. These paratroopers were using the parachute landing fall (PLF) technique that is described in Sect. 5 of this chapter. The paratroopers also only took approximately 730 ms to achieve maximum body-ground contact and up to 1.4 s to complete the entire roll-over during landing (see Sect. 5; [20]). Furthermore, this research demonstrated that landing absorption times were inversely proportional to descent velocity, an effect that can potentially magnify impact forces when load carrying paratroopers are landing at higher descent velocities. As static-line parachute landings involve a feet-first initial ground contact, necessitating rapid energy absorption by the lower limbs, it is not surprising that repeated high velocity parachute landings and their associated impact forces place the lower limbs at increased risk of injury [34]. Therefore, it is imperative that appropriate landing techniques are used to adequately absorb these high impact forces.

During the initial impact phase of a landing, the lower limb joints rotate with a pre-determined degree of neuromuscular control to attenuate the vertical ground reaction forces [35]. That is, lower limb eccentric muscle contractions allow hip, knee and ankle flexion to occur in an anticipated, pre-programmed manner to absorb the forces generated at impact. Forces experienced by the musculoskeletal system are then determined by how stiff or compliant the leg is in response to loading [36] due to the effect of joint range of motion and compliance on impulse time and energy absorption [37]. A selection of pertinent data reported in the literature related to the ground reaction forces generated and absorbed during landing movements, with the lower limbs being the primary source of force attenuation, is provided in Table 2.

As landing movements are highly complex, they require a multi-joint solution to effectively absorb the impact forces generated at ground contact [34, 38]. In essence, the lower limbs act largely as springs to rapidly and eccentrically absorb external loads imposed by landings. A low joint range of motion, particularly in the ankle, knee, and hip during impact absorption, is generally associated with a stiff-legged landing [37, 39]. Butler et al. [39] stated that an optimal level of leg stiffness was required to avoid injuries during landing activities. These researchers suggested that too much leg stiffness may be associated with bony injuries, because of the rapid rate of loading during the impulse, which results in higher forces. Conversely too little leg stiffness may be associated with a larger excursion of the joints, leading to soft tissue injuries [39]. Although lower limb loading is often considered in terms of simplified leg spring models [39–41], it is important to consider that energy absorption by the lower limb involves biological tissues that display viscoelastic characteristics and, therefore, influence the behavior of the system accordingly. For this reason, more complex mass-spring-damper models may more accurately represent aspects of lower limb loading responses during foot-ground impacts [42, 43]. Nonetheless, Alexander [44] concluded a thorough discussion of modeling approaches in biomechanics by stating that "Even the most complex of the models that I have discussed are simplified representations of reality" (p. 1434), acknowledging that no matter how considered a model is, one cannot account for every eventuality. Whittlesey and Hamill [45], also noted that the more complex mass-spring-damper models were not easy to apply or interpret and, although the lower limb is not a perfect spring, simple mass-spring models can be useful in understanding gross loading responses to foot-ground impacts. As such, for the sake of simplicity and often acknowledged as the best approach in understanding the major features of a model [44], leg-spring models are frequently applied two dimensionally by examining the effects of ground reaction forces on linear displacement in a vertical plane [40].

Farley and Morgenroth [40] demonstrated that leg stiffness during human hopping was directly proportional to ankle joint stiffness and far less influenced by knee stiffness. This is not surprising during a foot-first vertical ground impact where the ankle is the first major joint to encounter the vertical reaction force. Nonetheless, greater contributions to energy absorption are required by larger more proximal joints, such as the knee and hip, as landing velocities increase [46]. Research has shown that the rate of ankle injuries sustained during parachute landings is most sensitive to increases in vertical descent velocity [47]. This most likely reflects the limited capacity of the ankle, as the first major link in the lower limb chain, to cope with the high impact forces and fast loading rates typically

Table 2 Examples of studies that have provided ground reaction forces generated during landing movements

Landing movement	Relevant results	Reference
Barefoot single leg drop landings (6 female gymnasts). 2 techniques (stiff and soft). 3 types of gym mats used. 2 heights: 80 cm (4.0 m s^{-1}), 115 cm (4.8 m s^{-1})	Peak ground reaction force (GRF) ranged from 2.7 to 4.2 times body weight (BW) for 1 foot	[64]
Two-foot shod drop landings (3 trials per condition @ 50 cm height) onto 2 force platforms with and without vision (139 male US air assault soldiers)	Peak vertical GRF ranged from 3.4 to 3.8 BW per leg in vision and non-vision conditions	[65]
30 male US special operations forces soldiers ×15 simulated PLF landings. Performed during vertical drop landings in 5 different footwear/knee and ankle brace conditions onto FP from 3 heights of 1.07, 1.37 and 1.71 m (∼4.58, 5.18 and 5.79 m s^{-1}, respectively)	Effect of height on peak vertical GRF—8.9 to 17.3 BW for simulated parachuting landings from 1.07 to 1.71 m	[33]
2 foot landings from 3 heights and distances (n = 3, 81 trials each). Heights of 40, 60 and 100 cm (2.8, 3.4 and 4.4 m s^{-1}, respectively). 3 landing stiffness techniques used. All landings toe to heel	Peak GRF in 1 leg was 3.0 BW at 40 cm–6.6 BW for stiff leg landing at 100 cm	[66]
Drop landings with 2 feet onto 1 force platform. 5 expert male parachutists (>100 jumps each). 4 trials × 6 heights × 3 gaze directions. Heights of ∼20, 40, 60, 80, 100, 120 cm (2.0, 2.8, 3.4, 4.0, 4.4, 4.9 m s^{-1}, respectively)	Average peak GRF = 3.7 BW at 20 cm to 5.9 BW at 100 cm	[67]
Drop landings by well-trained female gymnasts (n = 9). Competition style 2 foot landings. 3 heights × 2 mats. Heights of 69, 125 and 182 cm (3.7, 5.0 and 6.0 m s^{-1}, respectively)	Peak GRF from 4 BW at 69 cm up to 9 BW at 182 cm	[34]
Drop landings (6 elite male gymnasts and 6 recreational male athletes). 3 heights of 32, 72 and 128 cm (2.5, 3.8 and 5.0 m s^{-1}, respectively)	Peak vertical GRF for gymnasts at 3 heights = 3.9, 6.3 and 11.0 BW; for recreational athletes = 4.2, 6.4 and 9.1 BW	[38]
Double back somersaults performed by elite gymnasts	Peak vertical GRF up to 18 BW	[38]
2 foot competition style (gymnastic) drop landing (10 female, 4 male intercollegiate gymnasts). 1 drop height of 69 cm (3.7 m s^{-1}) × 3 landing surfaces (no mat, stiff and soft mat)	Peak vertical GRF lowest for no mat condition and highest for stiff mat. Forces ranged from 3 to 6 BW	[68]

(continued)

Table 2 (continued)

Landing movement	Relevant results	Reference
6 elite male gymnasts performed 3 landing types—drop landing, front salto, back salto. From platform at height of 72 cm (3.8 m s^{-1})	Peak vertical GRF ranged from 3 BW (drop) to 5 BW (back salto)	[69]
Gymnast dismounting from the horizontal bar	Impact forces (GRF) up to 11.6 BW	[57]
Barefoot drop landings (6 males). 10 trials × 5 heights. Heights were 20, 40, 60, 80 and 100 cm (2.0, 2.8, 3.4, 4.0 and 4.4 m s^{-1}, respectively)	Mean peak vertical GRF for each height were 3.9, 4.7, 5.6, 6.9 and 7.9 BW	[35]
Barefoot drop landings (7 males, 1 female). 10 trials × 4 heights × 2 conditions (vision vs. no vision). Heights were 20, 40, 60 and 80 cm (2.0, 2.8, 3.4 and 4.0 m s^{-1}, respectively)	Vertical GRF occasionally reached 12 times BW for no vision trials and up to 8 BW with vision	[70]
Drop landings (10 female competitive gymnasts and 10 female recreational athletes). 10 trials × 3 heights—30, 60 and 90 cm (2.4, 3.4 and 4.2 m s^{-1}, respectively)	Peak GRF for gymnasts = 2.8, 4.1 and 5.7 BW; for recreational athletes = 2.2, 2.8 and 3.8 BW	[59]
20 paratroopers (1 female). 5 trials × 3 descent velocities. Heights were 32, 74 and 133 cm (2.1, 3.3 and 4.6 m s^{-1}, respectively)	Mean peak vertical GRF for each height was 5.8, 9.3, and 13.1 BW. Some participants averaged up to 18 BW, with one sustaining 24 BW on a single fast velocity trial	[20]
Barefoot (single leg) drop landings (33 males). 5 trials × 2 heights—32 and 72 cm (measured at 2.25 and 3.21 m s^{-1}, respectively). Low versus high dorsiflexion range of motion (ROM) comparison	Peak vertical GRF on single leg was 4.2 BW @ 32 cm and 6.9 BW @ 72 cm. No effect of dorsiflexion ROM	[71]
Drop landings (9 males). 5 trials × 3 heights × 3 techniques. Heights of 32, 62 and 103 cm (2.5, 3.5 and 4.5 m s^{-1}, respectively)	Mean peak GRF were 2.6, 3.3 and 4.7 BW for the 3 drop heights	[46]

experienced during static-line parachute landings. Conversely, while excessive horizontal wind drift, responsible for the horizontal component of descent velocity, can lead to trunk, head and upper limb injuries during a parachute landing, ankle injuries have been shown to be unaffected by horizontal wind speed [47, 48]. Consequently, while it is unclear precisely how much of the landing impulse and resulting impact force is absorbed by lower limb joints immediately following initial ground contact, as ankle injuries are the most prevalent injury in parachute landings, the notion of a leg spring model becomes central to any investigation of parachute landing techniques. During parachuting, the ground reaction forces generated at landing are also influenced by factors such as gravity, pendulum-like oscillations of the paratrooper and the hardness of the drop zone [9]. Any other variables that can increase a paratrooper's descent velocity, such as temperature, humidity and type of parachute, add to the total ground reaction force generated upon landing [3]. As most of these variables are beyond a paratrooper's control while descending, it is critical that the paratrooper maintains good body position on the landing approach and that the correct landing technique is employed [49]. Almost without exception, poor landing technique has been identified as the largest cause of landing injury in parachuting [9]. In fact, Ekeland [18] claimed that 70 % of all parachute-landing injuries resulted from poor landing technique.

5 The Parachute Landing Fall Technique

During the early days of parachute training, German and American parachute trainees were taught to land with their feet apart and then perform a forward roll across an outstretched arm to dissipate the kinetic energy existing at landing [9]. German parachutists were restricted to rolling forward upon landing because their parachute harnesses were attached at a single point at the centre of the upper back, causing the parachutist to land in a forward facing position [9]. British parachutists, however, descended in an upright position because the rigging lines of their parachutes merged onto risers (cords that connect the paratrooper's harness to the actual parachute), which attached to the parachute harness on the top of each shoulder [9]. This allowed the British to develop a landing technique in which the parachutist landed with their feet and knees together, and then rolled sideways. As this technique, known as the Parachute Landing Fall (PLF), was associated with significantly fewer injuries than the forward landing roll, the US Army adopted it in 1943 [5, 9].

Today, the PLF is a widely accepted method used by most military parachutists worldwide to reduce the risk of injury at ground contact ([9]; see Fig. 3). To perform a PLF, during the final stage of an aerial descent, the parachutist assumes a relaxed pre-landing posture. This posture is characterized by holding the feet and knees together, with slight flexion of the hips and knees [4, 49–51] to allow for optimal absorption of the initial ground reaction forces [28]. The chin should be placed on his or her chest, with the elbows tightly tucked in and hands clasping the risers [6], in readiness for ground contact.

On impact with the ground, the PLF involves a simultaneous touchdown of both feet with the lower limbs locked tightly together. It has been speculated that landing with the feet apart is likely to cause one foot to strike the ground before the other [9], such that the majority of landing forces are absorbed by one limb, with a subsequent increase in injury risk. Dual-limb ground contact is immediately followed by the paratrooper turning side on to the direction of landing to perform a

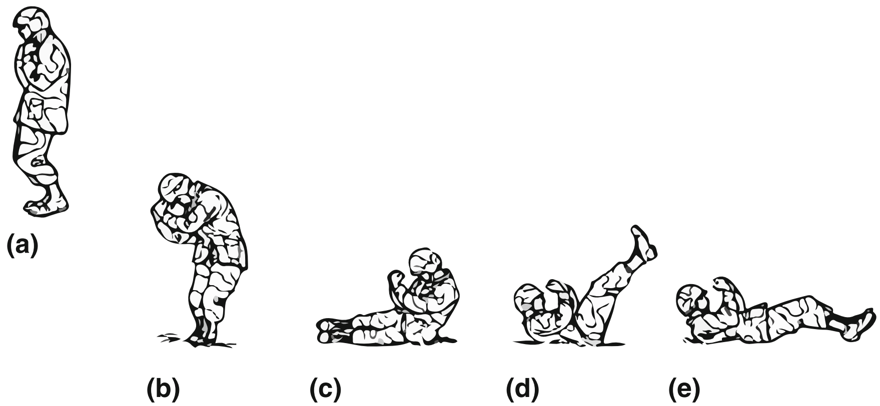

Fig. 3 Sequence of the correct parachute landing fall technique with side drift: **a** preparing to land, **b** initial ground impact with both knees and feet locked tightly together, **c** absorbing the landing forces over the lateral aspect of the calf, thigh and buttocks, **d** rolling across the latissimus dorsi region of the back, and **e** coming to rest at the end of the PLF (adapted from http://commons.wikimedia.org/wiki/File:Parachute_landing_fall.jpg)

sideways roll, involving five points of contact between the ground and the parachutist's body. The five points of body-ground contact begin with the feet, followed by the lateral aspects of the calf, thigh, and buttocks of the lead lower limb, with the latissimus dorsi region of the back on the same side as the lead limb being the final point of impact before the paratrooper dissipates the residual momentum by rolling over and coming to rest on the opposite side of the body ([20]; see Fig. 3). In theory, this sideways roll with multiple points of contact should enable the initial impact forces to be distributed across as much of the body as possible to disperse the kinetic energy carried into the landing by the paratrooper [6]. In turn, this should limit the need to dissipate all of the ground reaction forces via the lower limbs, thereby reducing the chance of injury [4, 9]. However, as stated above (see Sect. 4.1), it is important to acknowledge that the peak ground reaction forces occur at less than 100 ms [20] after initial ground contact, at a time when the paratrooper has still only made the first point of body-ground contact with their feet. Therefore, it is reasonable to conclude that a substantial portion of energy dissipation actually occurs through the lower limbs prior to the parachutists rolling through the other four points of body-ground contact. Once the roll has been completed and the parachutist is lying on the ground, he or she activates the canopy release so any remaining air is released from the canopy so the parachute can collapse and be removed, and the soldier is ready for ground operations [3].

Failure to perform the PLF correctly can lead to injury. For example, holding the feet too far forward can lead to the paratrooper absorbing the initial impact on their heels and then falling backwards to 'sit down' [23]. This causes the impact forces to be transmitted directly through the coccyx and lumbar spine, which can, in turn, cause compression-type fractures [6, 9]. Jaffrey and Steele [23] conducted a qualitative analysis of video clips, which depicted landings performed onto a drop zone by trainees during basic parachute training courses conducted throughout 2004. In almost 70 % of the assessed landings, trainees held their feet too far forward in preparation to land, rather than having them vertically aligned with the body [23]. In the same cohort, although most (88.4 %) held their chin on their chest correctly, ~35 % held their knees too flexed in preparation to land, 65 % did not 'turn their feet off' appropriately in order for the long axes of their feet to be perpendicular to the line of drift, 47.5 % had their feet apart rather than together at impact, and a PLF roll was absent in 78.7 % of the assessed landings [23].

Even when the PLF is performed properly, the injury risk can be high. For example, during the PLF, the paratrooper's ankle that is furthest from the direction of the PLF roll is subjected to a pronation/eversion moment, which can result in an ankle fracture [9]. Conversely, irrespective of the feet being held tightly together, substantial sideways drift, such as that caused by high winds, can force the ankle closest to the direction of the PLF roll into excessive inversion/supination and, in turn, injure the ankle ligament complex, fracture the tibia or fracture the tibia and fibula [9].

Although the concept of distributing the landing forces to reduce injury potential is simplistic, when the PLF is broken into phases, neuromuscular and mechanical strategies required to achieve effective force distribution are extremely complex. From Sect. 4.1, it is apparent that the ground contact phase of landing, occurring immediately after impact, determines lower limb loading via ankle and leg stiffness and that the stiffness of the leg spring is an appropriate representation of the average stiffness of the entire musculoskeletal system during this phase [40]. Furthermore, it is widely accepted that lower limb loading increases with increases in both landing velocity and leg stiffness [46] and that at higher landing velocities, greater knee and hip flexion are likely to be required to mitigate the effects of the vertical ground reaction forces generated at foot-ground contact in drop landings [34, 46]. Unlike isolated drop landings, however, the PLF involves continued dissipation of momentum and force during the rolling phase and requires that paratroopers change the direction of force from an axial direction, very quickly into a rotational and somewhat torsional direction, prior to rolling onto the additional four points of the body [52]. Not only does the initial ground contact phase of the PLF determine lower limb loading, but it also determines how quickly the parachutist goes into the roll, the magnitude of reaction forces encountered in subsequent phases, as well as the overall force encountered from the landing. Therefore, research pertaining to isolated drop landings has only limited relevance to understanding factors affecting performance of the PLF.

Paratroopers absorb the initial impact of a landing by eccentrically dorsiflexing their ankles and flexing their knees and hips [28]. A parachute landing field study conducted by Henderson et al. [49] revealed that for best PLF performance, maximum knee flexion had to occur early, as this allowed for an extended execution of the entire roll. Although this suggests a stiff landing during the initial ground contact phase, overall, forces imposed on the body may be minimized relative to a less stiff PLF landing. Henderson et al. [49] also postulated that minimizing knee flexion, although increasing the vertical ground reaction forces, may help to reduce patellar tendon loading. Hoffman et al. [51] found that more experienced paratroopers displayed stiffer landings during drop landings compared to their less experienced counterparts. The authors speculated that this increased stiffness might be necessary to more efficiently dissipate the overall landing force by providing a more expedient transition to the rolling phase of the task. It should be noted, however, that this was not tested with a full PLF movement task and therefore their conclusions need to be considered with some caution. In light of the fact that lower limb injuries account for most injuries sustained during parachute landings (see Sect. 3.2), the correct amount of leg stiffness poses a real dilemma to PLF instructors. Controlling the rate of roll-over by regulating leg stiffness may safeguard some body parts while exposing others to increased injury risk.

5.1 International Variations in the Parachute Landing Fall

Previous studies have shown that injury rates and types differ between nations. For example, Craig et al. [13] showed that in a joint military operation, UK soldiers sustained more injuries overall (3.8 injuries per 1000 aircraft exits) than the US forces (2.9 injuries per 1000 aircraft exits). In addition to differences in overall injury incidence, there were different injury patterns whereby the UK soldiers had significantly more lower extremity and closed head injuries and significantly more multiple injuries than their US counterparts [13]. Although the authors noted it was difficult to determine the cause of these differences in injury statistics, it is interesting to note that subtle variations of the PLF exist between national military organizations, particularly with regard to foot pitch angle at initial ground contact [28]. For example, the Australian Defence Force paratroops are taught to hold their feet slightly dorsiflexed to land flat-footed upon ground contact [6], whereas US paratroopers today use a plantar flexed, toes-first foot pitch and make ground contact first with the balls of the feet [5].

It has been speculated that landing with the feet plantar flexed is likely to transmit the landing forces through the metatarsal bones (which may fracture) toward the articular surface of the tibia, possibly causing the posterior lip to fracture [9]. Only one study, however, has systematically investigated the effects of variations in foot pitch at initial ground contact on PLF technique under realistic ground training conditions of vertical and horizontal descent velocities. Whitting et al. [28] investigated whether differences in foot pitch affected parachute landing technique by monitoring kinematic, ground reaction force and muscle activity data for 28 (mean age = 30 ± 7 years; 1 female) skilled paratroopers who performed parachute landings (descent velocity 3.3 ± 0.2 m s^{-1} with a constant horizontal drift of 2.3 ± 0.01 m s^{-1}) from a custom-designed monorail system. During the 134 trials analyzed for the study, 69 % of the total landings involved initial ground contact with the ball of the foot, which is in direct contrast with the neutral flat-footed posture at ground contact taught to these Australian paratroopers. Foot-pitch at ground contact significantly affected PLF technique, whereby each foot pitch group used an entirely different biomechanical strategy to absorb the initial impact forces during landing. That is, those participants who used a ball of the foot foot-pitch displayed significantly greater knee extension and ankle plantar flexion and a larger range of knee and ankle motion during impact absorption [28]. Furthermore, the ball of the foot foot-pitch group displayed a significantly lower vertical ground reaction force at ground contact (8.4 ± 1.4 BW vs. 10.8 ± 0.8 BW; $p > 0.001$), and a less rapid rate of loading than the flat-foot foot-pitch group (37.4 ± 5.9 ms vs. 20.1 ± 2.1 ms from initial ground contact until the peak resultant force time; $p > 0.001$). Interestingly, there was no statistical between-group difference in the time taken to make the standard five points of body-ground contact and both groups used a reasonably consistent neuromuscular recruitment strategy [28]. It was postulated that using the ball of the foot first technique was a protective adaptation to reduce excessive lower limb loading during initial ground contact. That is, it allows the paratroopers to use an extra segment during the impact absorption phase of landing, which can assist in force absorption by increasing the impulse time and, in turn, reducing the absolute load in this phase of the landing [28]. This notion is further discussed in Sect. 5.2.2 (Fig.4).

Chinese paratroopers are trained to use a half-squat parachute landing and not the PLF technique [53]. Similar to the PLF, half-squat landing involves contacting the ground simultaneously with both feet to diminish the energy of falling [54]. Instead of rolling, however, the paratroopers contact the ground with both hips, knees and ankles all flexed, keeping these joints flexed until their trunk regains balance, and they can resume a neutral stance position [54]. Despite differences in

Fig. 4 Paratrooper performing the parachute landing fall technique onto a force platform to assess the ground reaction forces generated at landing (taken during the study of Whitting et al. [28])

techniques, a prospective study of all military parachuting injuries recorded for Chinese Air Force cadet pilots (n = 168 injuries recorded in 153 cadet pilots) during basic static-line parachuting training between 1988 and 2008 [15, 16], showed injury profiles and mechanisms that were similar to their Western counterparts. However, for reasons discussed previously, it is difficult to make comparisons between studies due to a multitude of differences in data collection and treatment techniques with regard to injury definitions.

5.2 Training the Parachute Landing Fall

Irrespective of discrepancies pertaining to the exact technique, learning to land safely is critical as appropriate training and attention to detail can substantially reduce the risk of sustaining a parachuting injury [15, 24]. Training should be structured so that performance of the correct technique becomes automatic, even in a crisis or when performing a hazardous mass tactical, combat equipment assault at night during inclement weather [9, 13, 17].

5.2.1 Training Program Structure

Training for military parachutists is typically longer and more intensive than that required for civilian parachutists because the extreme demands and skill involved in being able to participate in a massed parachute assault at night are substantially greater than those required for a novice sport descent [4, 9, 24]. In addition, military training needs to ultimately lead to imprinting the biomechanical skills involved in executing a safe landing so that the basic drills become automatic, irrespective of external distractions [9]. For this reason, substantial time during training should be devoted to demonstrating landing techniques [26], as well as ensuring sufficient actual descents are experienced to ensure paratroopers can perform correct PLF technique in real descents. Although all paratroopers require experience jumping out of aircraft onto the drop zone, performing a high number of actual jumps in the field to improve technique is not feasible due to both high costs and the fact that it could result in more chronic injuries [7]. For this reason, military static-line parachute training incorporates a substantial component of ground training to develop the landing technique of trainees [7]. It has also been advocated that after basic parachute training is completed, that paratroopers maintain their skills by completing frequent military static-line parachuting training activities throughout a year (>three descents/year) and/or extensive ground training prior to conducting military static-line parachuting over land [6].

Adaptation to increases in descent velocity and training experience involve the development of mechanical and neuromuscular strategies, which enable parachutists to optimally perform the PLF technique [55]. As stated by Santello and McDonagh [35], during landing movements the motor control system must be able to predict the vertical ground reaction forces likely to be encountered on ground contact and activate the absorption system appropriately, providing the optimum degree of limb compliance. In a high-speed collision with the ground, reflex patterns are not quick enough to contend with force dissipation [35]. This leaves little doubt that experience through effective training is necessary to equip paratroopers with the ability to absorb loads imposed by a parachute landing.

Military parachute training schools the world over teach trainee paratroopers the PLF technique, albeit with slight between-school modifications [2, 3, 9, 56]. The Australian Military Parachute Training School (PTS) conducts several 3-week courses in static-line parachuting, for novices, each year. The goal of this training is to provide trainees with competency in the operational aspects of military static-line parachuting and approximately 60 soldiers are trained per course [23]. The obvious implication from this example is that a substantial number of military personnel, both in Australia and worldwide, are exposed to the risks associated with static-line parachuting during training and beyond as they engage in operational activities. The potential burden on personnel, military organizations and health care systems for preventable catastrophic injuries would likely be substantial should training programs be inadequate in preparing personnel.

Using the Australian Military PTS as an example of training progression, training begins in a gymnasium with floor exercises designed to teach trainees the 5-point PLF roll (see Fig. 5a). Trainees then progress to a slightly more complex scenario, such as the wheel trainer displayed in Fig. 5b, where they are suspended below a swinging wheel. This type of progression enables trainees to learn to adopt the correct 'prepared to land' posture, with their feet less than 1 m above padded mats on the gymnasium floor (see Fig. 5b). The swinging wheel trainer also acts to impart a small degree of horizontal velocity before the trainees allow themselves to drop onto the mats and practice using the PLF roll that they learned during the initial floor exercises. Due to their close proximity to the floor on release, vertical descent velocities experienced by trainees on the wheel trainer, estimated at between 2.1 and 3.4 m s^{-1} [23], are considerably lower than those experienced under a canopy in the field. Other progressions before attempting an actual aerial parachute landing onto the drop zone, can involve descents from various apparatus, such as a 30 m tower used at the Australian Military PTS (see Fig. 5c), whereby paratroopers are fixed to a cable that controls the trainee's vertical descent rate (usually between 2.7 and 3.9 m s^{-1}), with a small component of horizontal velocity [23]. The progression to an apparatus such as the tower, allows paratroopers to experience a controlled descent, albeit at relatively low velocities, while being exposed to a sense of height from the ground.

Jaffrey and Steele [23] investigated training methods used at the Australian Military PTS to determine whether improvements could be made to either the PLF technique itself or the methods used to teach the current PLF technique. Investigation by these researchers also included observation and analysis of equipment used during PLF training in order to ascertain whether equipment modifications could assist in decreasing the risk of parachute training injuries. The results of this study are detailed in a report titled "Landings during 2004 basic

Fig. 5 Ground training progressions at the Australian Military Parachute Training School, Nowra, New South Wales: **a** floor exercises on gymnasium mats; **b** wheel trainer exercises in the gymnasium; and **c** training tower landing while suspended in a harness

parachute courses: Common technique faults and injuries" [23]. One of the key findings of this report was a distinct delineation between vertical velocities achieved during ground training activities and those experienced under canopy on the first real aerial descent. It was reported that ground training apparatus restricted the vertical descent velocities achieved by trainees to between 0 and 3.4 m s^{-1}, whereas aerial parachute descents onto the Drop Zone resulted in vertical velocities of between 4.6 and 6.7 m s^{-1}. A study involving US paratroopers has shown that simulated parachute landings with vertical descent velocities within this range can result in ground reaction forces in excess of 17 times body weight being generated [33]. Vertical velocities experienced by trainees during ground training at the Australian Military PTS at the time this report was commissioned, therefore, were considerably less than those encountered when descending under a canopy for the first time [23]. Since this report, further research has been conducted to determine the effects of varying vertical descent velocity on PLF technique ([20]; see Sect. 5.2.2). Based on recommendations arising from this research, ground apparatus that can vary horizontal and vertical velocities to simulate realistic descent velocities was designed. Consequently, paratroopers at the Australian PTS can now experience an additional ground training progression that involves simulated PLF landings at more realistic descent velocities. This practice is consistent with the advice of Salai et al. [52], who stated that the best way to prevent parachute landing injuries was to ensure that novices perform landings during ground training, focusing on correct technique while accurately replicating real aerial scenarios, particularly with respect to descent rates. Clearly, it is essential that paratroopers are properly trained to handle landing impacts associated with realistic vertical descent velocities.

Aside from learning to land safely by correctly employing the PLF roll, during the ground-training phase of a basic course, military trainees will also learn the necessary basics regarding the parachute harness and rigging. This type of training allows paratroopers to engage with use of the harness and to experience being suspended below the rigging that extends to the canopy. Furthermore, while experiencing suspension in the parachute harness during ground training, paratroopers are drilled in other important tasks, such as operating the rigging and 'risers' that are used to provide limited control of velocity and steerage (see Sect. 2), and how to maintain the correct descent posture while positioned in the harness.

5.2.2 Vertical Descent Velocities and Landing Technique

It is widely accepted that ground reaction forces, and therefore lower limb loading, increase during parachuting landing tasks with increases in landing velocity [20, 33]. In static-line parachuting there is little a paratrooper can do to reduce their descent velocity, making efficient lower limb biomechanics crucial to moderate the high impact forces [28]. It is therefore imperative that military static-line parachute training involves activities that prepare paratroopers to be able to perform the PLF under realistic decent velocities.

Although there is limited research pertaining to parachute landings, the biomechanics of drop landings under different conditions of height and velocity has been studied extensively [35, 38, 46, 51, 55, 57, 58]. Several of these studies have shown that, although athletes display consistency in the temporal aspects of muscle sequencing as landing velocities increase, they use different kinematic landing strategies for absorbing loads imposed by the higher velocities [34, 38, 59]. Despite this wealth of landing-related research, only limited research has systematically investigated the effects of velocity on performance of the PLF, but with most landing studies having used subjects from non-parachuting populations or, where parachutists were used, the movement task did not replicate the PLF [51]. One of the most comprehensive biomechanical studies of parachute landings [33] reported results based on PLF rolls that were performed from drop boxes without a standardized or realistic horizontal velocity as experienced by paratroopers in the field. Furthermore, although one study observed parachute landings during a military parachute course, descent rates and modes of drift were not standardized [49].

Therefore, particularly with respect to differences in vertical descent velocity, there was little understanding of the biomechanics of the PLF technique until the research of Whitting et al. [20].

Whitting et al. [20] collected kinematic, ground reaction force and muscle activity data for 20 Basic Parachute Course trained personnel (19 men, 1 woman; mean age = 32 ± 8 year; height = 176 ± 67.3 cm; mass = 83.0 ± 10.2 kg) while they performed simulated parachute landings using the PLF technique. The landings were performed using a custom-designed monorail apparatus, with a constant horizontal drift velocity (2.3 m s^{-1}) and at three realistic vertical descent velocities: slow (2.1 m s^{-1}), medium (3.3 m s^{-1}), and fast (4.6 m s^{-1}). Descent velocity significantly affected most of the biomechanical variables characterizing the PLF technique. That is, as descent velocity increased, the participants activated their antigravity muscles significantly earlier prior to initial ground contact and then contacted the ground with their knees more extended and their feet more plantar flexed. This strategy likely allowed the paratroopers to absorb the significantly higher impact forces (see Table 2) generated during conditions of greater descent velocity, over a longer period than they otherwise would have experienced, by using greater ankle and knee motion during impact absorption [20].

As these technique modifications were more evident as descent velocity increased, it is postulated that the modifications were protective adaptations used to reduce excessive lower limb loading during initial ground impact [20]. Interestingly, although the participants tended to land flat-footed during the slow velocity trials, reflecting the technique taught during Australian Defence Force Basic Parachute Courses, they tended to neglect their trained neutral foot position at landing, and instead plantar flexed the foot to contact the ground with the balls of the feet progressively more as descent velocity increased [20]. In fact, 78 % of landings in the fast descent condition involved plantar flexed feet. This technique modification added an extra segment to the initial impact phase and it was postulated that this would have influenced absorption of the ground reaction forces as discussed previously.

In a follow up study Whitting et al. [28] compared the landing biomechanics displayed by individuals who consistently used a flat-footed technique and individuals who adopted a plantar flexed foot position, in a cohort of 28 trained paratroopers performing simulated PLF landings at a moderate vertical descent velocity (3.4 m s^{-1}). Peak ground reaction forces occurred significantly earlier and were significantly higher in the paratroopers who used the flat-footed technique because they performed the initial absorption phase of the landings with significantly reduced knee and ankle ranges of motion, resulting in a significantly shorter period of time for the impulse during this phase of landing. The landing kinematics displayed by the flat-footed group suggested these paratroopers used a stiffer landing with faster loading rates. Henderson et al. [49] and Hoffman et al. [51] speculated that reducing knee flexion early in the PLF to expedite the PLF roll may be beneficial to reducing overall landing forces, but this notion was not supported by the experimental findings of Whitting et al. [28]. As stated earlier, injury statistics demonstrate that lower limb injuries occur most frequently during PLF landings and that the ankle and knee joints are the most vulnerable (see Sect. 3). Furthermore, due to mechanisms discussed in Sect. 5, ankle injuries are likely to occur during the initial impact phase when ground reaction forces are high. It seems intuitive that strategies that can safely reduce ground reaction forces during the early impact absorption phase of the PLF may be advisable. Nonetheless, these conclusions remain speculative and require further investigation.

Irrespective of potential injury implications for varying foot pitch during initial impact in PLF landings, as paratroopers display a significantly different PLF technique with increasing descent velocity [20], it is recommended that PLF training programs should include ground training activities with realistic vertical descent velocities. This will better prepare trainees to withstand the impact forces associated with initial aerial descents onto the drop zone and, ultimately, minimize the potential for injury.

5.2.3 Parachuting Experience and Landing Technique

Aside from vertical descent rates, parachuting experience has also been shown to influence landing strategies employed by paratroopers. For example, Hoffman et al. [51] showed that experienced and novice paratroopers displayed significant differences in both the ground reaction forces generated at impact and the time to peak force when performing drop landings from varied take-off heights. Although participants in this study were not subjected to horizontal drifts characteristic of parachute landings and did not perform a typical PLF, results demonstrated possible differences in landing strategy with variations in training experience. The experienced paratroopers displayed a much stiffer landing strategy, even though each group had statistically similar results for leg strength and power. Hoffman et al. [51] postulated that the experienced participants used leg power by optimally tensing their leg extensor muscles prior to landing, thereby reducing the time to peak force during the initial ground contact phase of the landing. In apparent contrast, Henderson et al. [49] found that a period of myoelectric silence in the lower limb muscles following initial landing impact was exaggerated with experience, as well as increased descent velocity. However, due to the dearth of similar studies in the area of parachute landing biomechanics, further research is required to investigate the effects of different vertical descent velocities on landing technique and how this is influenced by jump experience.

6 Preventative Strategies to Reduce Parachuting Injuries

6.1 Ankle Braces and Parachute Landing Fall

As highlighted in Sect. 3.2, the ankle is the most commonly injured anatomical site during military static-line parachuting. Ankle injuries can also have a negative impact on a soldier's well-being and, possibly, on their career progression [60]. In response to the frequency and negative impact of ankle injuries, an outside-the-boot parachute ankle brace (PAB) was developed to reduce the incidence of ankle injuries. The PAB (Aircast, NJ, USA) consisted of a hard plastic outer shell lined with air bladders, which padded the medial and lateral malleoli, to prevent extreme ankle inversion and eversion while allowing plantar flexion and dorsiflexion [14]. Trials have consistently shown that the risk of ankle injury is reduced when the soldiers wear a PAB during parachuting training, with no accompanying increase in the risk of other traumatic injuries [14, 22, 60]. For example, a randomized trial conducted at a US Army Airborne School demonstrated that the PAB reduced ankle sprains among 745 trainees by 85 % [27]. Schmidt et al. [14] compared the hospitalization rates for ankle, musculoskeletal, and other traumatic injuries incurred by 223,172 American soldiers who were trained during 1985–2002 in distinct time periods during which PAB use was mandatory or not. The researchers found that, of the 939 parachuting-related hospitalizations during the study period, the odds of experiencing an ankle injury were twice as high when training occurred during intervals when the use of an outside-the-boot ankle brace was not required [14]. A summary of studies examining the parachute ankle brace is provided by Knapik et al. [61]. In fact, in their systematic review, Knapik et al. [61] found that risk of ankle injury or ankle sprain was more than twice as high among individuals not wearing the ankle brace while risk of ankle fracture was about 1.8 times higher among those not wearing the brace. Importantly, the risk of other lower limb injuries was not significantly elevated among those who wore the PAB [60, 61]. These and other consistent findings clearly establish that using the PAB is a cost-effective intervention that reduces the incidence of ankle injuries, ankle sprains, and ankle fractures during military parachuting by about one half and, in turn, can reduce individual soldier morbidity and financial costs to the military [60, 61]. In fact, Schmidt et al. [14] estimated that the ratio of expenditure ($30,000 per year USD) for braces to hospital care and rehabilitation costs saved ($835,000 per year) was 1:29. Interestingly, despite this evidence, use of the PAB in some sectors of the military has not been adopted or has been discontinued due to anecdotal reports claiming increases in risk of other types of injury, and the cost of obtaining and periodically replacing the PAB [60].

Although the impact of brace wearing on injury incidence has been well documented, less evidence has examined the mechanisms by which braces work. It is likely that the PAB reduces ankle injuries, particularly fractures and sprains, by strengthening the carrying capacity and stability of the ankle joint and associated bones, preventing excessive ankle inversion on ground impact, as well as by increasing sensory awareness or proprioception [3, 15]. Knapik et al. [61] speculated that ankle braces acted as a splint, providing stiff medial and lateral support to the ankle. The authors postulated that this splinting likely reduced the velocity and/or extent of ankle inversion or eversion at ground contact, thereby preventing excessive ankle motion that often leads to injury [31, 61]. It is possible that a brace also transfers some of the force that would be transmitted from the ankle joint to the lower calf, which can absorb force with much less risk of injury than the ankle joint [61]. Schmidt et al. [14] concluded that approximately 40 % of ankle injury hospitalizations experienced by US Army Airborne School trainees could be avoided if wearing a PAB during training was mandated. Despite evidence that the PAB is a safe, effective and cost effective prophylaxis, wearers of the brace have made negative comments related to heel strap slippage and a lack of comfort, necessitating design modifications, particularly to hold the PAB in place during PLF [31].

6.2 Shoes and Injuries

One of the main equipment items at the interface between the drop zone and the parachutists at landing is their footwear. Despite this, very little research has examined the effects of footwear on military static-line parachuting injuries. Guo et al. [15] noted that protective boots with wide soles, cushioning insoles, and ankle braces, were better than an early generation boot in reducing parachuting injury rates. They speculated that wide soles could stabilize the landing, while cushioning insoles could reduce the landing impact force. However, these findings were for Chinese paratroopers, who are trained to land on their feet, using the half squat technique. The effect of boots on landing injury rates and PLF technique warrants further investigation.

7 Recommendations for Future Research

Military static-line parachuting is a highly tactical and hazardous activity, with a well-documented injury risk. Due to the high impact forces encountered when a parachutist lands, the lower limbs carry the highest risk of injury, particularly when poor landing technique is used. Although numerous studies have investigated factors associated with the occurrence of injuries during training and operations, these investigations have predominantly focused on injury surveillance and statistical analysis of injury data, with few well-controlled studies having examined the injury mechanisms or rationale behind preventative strategies. In fact, there is a paucity of experimental studies that have investigated the biomechanical demands of parachuting, upon which to develop evidence-based guidelines for landing technique or training. Although one study was located which used instrumentation (two triaxial accelerometers plus surface electromyography) to quantify parameters during actual skydives [62], this study was related to evaluating decelerations and muscular responses during parachute opening shock. Niu and Fan [53] used instrumentation to examine the biomechanical effects of terrain stiffness on the half-squat parachute landing (HSPL). Ground reaction forces, lower limb muscle activity and motion were quantified for 16 participants as they performed landing tasks. The participants, however, were university postgraduate students rather than military personnel, who landed on variations of an ethylene-vinyl acetate insole mat rather than a surface that reflected the characteristics of a drop zone, and the peak vertical ground reaction forces generated at landing were relatively low (5.75 ± 2.21 BW for men and 4.78 ± 1.92 for women when landing on a 0 mm thick surface). Similarly, Li et al. [54] quantified foot plantar pressure distributions, using an in-shoe pressure measurement system, displayed by 20 elite male paratroopers (22.6 ± 5 years of age) as they landed on a hard surface versus a soft surface in a half-squat posture. However, the protocol required the participants to jump off a platform that was only 60 cm high and therefore did not realistically replicate the demands of parachuting (see Fig. 6).

Fig. 6 Jumping off a 60 cm box will not replicate the demands associated with trainees learning military static-line parachuting onto a drop zone

Based on this review and the paucity of experimental studies that have investigated the biomechanical demands of parachuting, the following recommendations are made for further research into the PLF technique and training methods:

1. *Parachuting landing technique*: A detailed biomechanical investigation of parachute landing techniques, including a comparison of the forces involved in the various parachuting landing techniques (e.g. PLF vs. the half squat landing technique), is recommended. Such information is required to be able to provide systematic evidence upon which parachuting landing technique guidelines can be developed.
2. *Foot pitch*: Due to the variations in foot posture recommended by military personnel around the world, it is recommended that a detailed biomechanical investigation of the effects of foot pitch on ground reaction force attenuation, as well as implications for its use in minimizing injury risk is conducted. Such investigations should include substantial longitudinal assessments of injury risk. As landing on the ball of the foot with a plantar flexed foot pitch may expose paratroopers to increased pressure in the metatarsal bones, as well as destabilize the ankle joint relative to a flat-footed landing, this should also be addressed by further research. With implications for ankle stability in such investigations, this research should also address the efficacy of ankle braces and alternative footwear to be used in conjunction with altered foot postures [20].
3. *Characteristics of the paratroopers*: As the impact forces generated at ground contact are extremely high, it is recommended that research is performed to determine the body morphology, strength and flexibility characteristics required by potential paratroopers to avoid injury. This would enable appropriate screening methods to be developed by the military to reduce injury risk. For example, it has been suggested that parachute landing casualty rates may be reduced if a bodyweight restriction on paratroopers was established, given the association between increased bodyweight and higher landing forces [6]. However, the interaction between other factors, such as muscularity and strength, would need to be factored into any such study, as the relationship between body weight and military parachuting injuries has been inconsistent [3]. Furthermore, given that static-line parachutes have a load limit, there is a potential for paratroopers with lower body weights to carry greater relative equipment loads than heavier paratroopers. Therefore, the effect of relative equipment and paratrooper loads on injury potential should be investigated.
4. *Training*: A more extensive investigation of current PLF training apparatus and methods should be performed, with the intention of providing trainees with exposure to the most appropriate training activities and progressions to ensure they are adequately prepared for real descents onto the drop zone. Factors such as the specificity, intensity and frequency of ground training, and the progression in exposure to variations in factors such as vertical descent velocities, should be further investigated.

5. *Operational equipment*: Detailed analysis of carrying techniques for operational equipment, such as rucksacks, and how this affects PLF techniques is also recommended [8].
6. *Protective equipment*: Dedicated studies focused on improving landing safety using different protective equipment (such as ankle braces) is recommended and likely to yield high returns [8]. Protective equipment should ultimately be examined in an operational setting, as well as in the laboratory, to provide a comprehensive assessment of the equipment's effectiveness in terms of both performance and injury prevention under realistic conditions [63].
7. *Head injuries*: Recent studies have shown an increase in the incidence of closed head injuries/concussions during military static-line parachuting [5]. The prevention of head injury in parachuting has not been thoroughly explored and therefore research investigating traumatic brain injury prevention and treatment is recommended [8]. For example, although jumpers wear combat helmets during all jump operations, these helmets were designed primarily for ballistic protection and not specifically for protecting the head during ground impacts [5]. It is recommended that helmet design modifications be investigated to improve head protection for military static-line parachuting.

Ultimately, any changes to current practice in landing technique, how it is taught, and whether protective equipment is introduced, should ideally be monitored to determine the effect of these factors on injury rates and paratrooper performance. These studies should be well controlled, prospective rather than retrospective in nature, with the statistical design accounting for the interaction between the variables. It is also strongly advocated that international research conform to a consistent injury definition and method of describing associated details, such as anatomical distribution and type, to allow better between-study comparisons [9]. This will ensure that evidence-based guidelines can be developed, particularly in relation to landing technique and how this is trained, in order to minimize injuries associated with landings during military static-line parachuting in subsequent operations.

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