Preventing ischial pressure ulcers: I. Review of neuromuscular electrical stimulation

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Abstract. *Objective:* Pressure ulcers (PUs) are common and debilitating wounds that arise when immobilized patients cannot shift their weight. Treatment is expensive and recurrence rates are high. Pathophysiological mechanisms include reduced bulk and perfusion of chronically atrophic muscles as well as prolonged occlusion of blood flow to soft tissues from lack of voluntary postural shifting of body weight. This has suggested that PUs might be prevented by reanimating the paralyzed muscles using neuromuscular electrical stimulation (NMES). A review of the published literature over the past 2 decades is detailed.

Outcomes: Historically gluteus maximus (GM) has been an important target for NMES, but results have been difficult to interpret and suitable technology has been lacking.

Conclusions: NMES of the buttock muscles appears to be valuable in terms of its trophic effects, improving vascularity and soft tissue bulk. It remains unclear, however, whether GM can actually achieve sufficient unloading of normal forces to permit blood flow in the capillary beds of the skin and muscle. Analysis of the skeletal biomechanics is required to assess the relative value of GM vs. hamstring (HS) hip extensors in this regard.

Keywords: Decubitus ulcer, neuromuscular electrical stimulation, pressure ulcer prevention, gluteus maximus, hamstrings, spinal cord injury

Abbreviations

DTI	Deep Tissue Injury
FES	Functional Electrical Stimulation
FMS	Functional Magnetic Stimulation
GM	Gluteus Maximus
HS	Hamstrings
IT	Ischial Tuberosity
NMES	Neuromuscular Electrical Stimulation
PU	Pressure Ulcer
SARS	Sacral Anterior Root Stimulator
SCI	Spinal Cord Injury

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1. Introduction

This is the first of three papers regarding the potential for chronic neuromuscular electrical stimulation (NMES) to prevent ischial pressure ulcers in paraplegic patients. This paper reviews the clinical problem and previous attempts to use NMES for this purpose. The two companion papers: 1) describe the musculoskeletal biomechanics, and 2) report on a pilot clinical study of a new technology that enables a recommended treatment strategy.

2. Clinical scope and outcomes

Pressure ulcers (PUs) are a debilitating pathology that can result in severe morbidity (e.g. sepsis, osteomyelitis, renal failure, cardiac failure) [70]. Approx-

imately 30% of immobile patients develop PUs [54]. The buttocks is by far the commonest region affected, accounting for over 70% of all PUs (46% sacral; 26% ischial) [39]. Groups particularly at risk are patients with spinal cord injury (SCI) and the elderly who have lost mobility from stroke, dementia, frailty, Parkinson's disease, etc. The prevalence of SCI in the US was ∼262,000 (231,000–311,000) in 2009, with an incidence of ∼12,000 new injuries per year (40 per million US) [57]. The incidence of PUs in SCI is ∼33.5% during initial rehabilitation, and up to an additional 30% in the 30 years post-injury [56]; along with a similar prevalence [23]. In SCI ∼45% of these are ischial/sacral, with 11.3% at Stage III/IV (III = full thickness tissue loss; IV = exposed bone, tendon or muscle) [56].

Many preventive and therapeutic modalities are employed, but to little avail. For *prevention*, the current mainstay is load reduction, through regular weight-shifting together with passive cushions and varieties of pneumatic devices over the years [2, 63]. Immobile patients must change position every 2 hours when recumbent and every 15–20 min when seated [71]. This high demand results in poor compliance, especially in patients who do not feel pain or discomfort, or are ineffective at independently shifting their weight [28]. For *treatment*, the conservative mainstay is prolonged passive load reduction and medical support. Aggressive surgical repair is required, however, in as many as ∼70% of Stage III/IV PUs [12]. Flap reconstruction to provide well-vascularized, bulky tissue to cover bony

prominences was pioneered by Davis in the 1930s [18]. Since 1970, gluteal flaps have been used widely, as originally described by Ger [21, 50]. Although still the best option available, post-operative recurrence rates are as high as 61% within the first year of repair, and vary widely [19, 65] (Table 1). The literature, although fragmentary, confirms that patients frequently resume sitting on their repaired sites, thus reinitiating all of the etiological mechanisms. Furthermore, the flap tissues in SCI are not as healthy, thick, vascularized or resistant to PUs as in non-SCI subjects.

The high recurrence rates compound costs of $50–80K per incident. Furthermore, hospital stays increase 3–5 fold vs. age- and pathology-matched non-PU patients. The cost of treating *all* PUs in the US has been estimated to exceed $56B annually (average increased hospital stay of 21.6 days at $2,360 per day, in almost 1.1 million patients per year) [53].

3. Pathophysiology

Pressure ulcers are associated with both pressure and shear in soft tissues [75]. In addition to the capillary occlusion that results from both of these factors [25, 45, 68] many other etiological mechanisms contribute too, including lymphatic occlusion, reperfusion injury, and tissue deformation [1, 3, 26, 64]. Finite element modeling of the latter, predicts that as dead cells accumulate, the resultant microstructural heterogeneity further deforms surviving cells, thereby aggravating

Table 1
Recurrence rates after surgical flap repairs for PUs over past 2 decades (sampling of papers)

Year	Group	n	Recurrence rates
1992	Disa, 1992	66 flaps	61% PUs and 69% pts, at mean of 9.3 mo.s despite 80% healed at discharge
1994	Evans, 1994	22 paraplegics	82% surgical site, and 64% new sites
1997	Foster, 1997	139 ischial PUs in 114 consecutive pts over 16 yrs	17% at mean of 10.7 mo.s prior flap reconstruction had been performed in 60%
1998	Kierney, 1998	268 PUs in 158 pts over 12 yrs	21% ischial flaps at mean of 3.7 yrs 23% all flaps in SCIs (24% paraplegics; 20% tetraplegics)
1999	Tavakoli, 1999	23 pts	57% paraplegics, 33.3% tetraplegics, at mean of 62 mo.s paraplegics responsible for their own weight-relief may be less fastidious than tetraplegics who require caregivers?
2000	Schryvers, 2000	191 ischial PUs over 20 yrs	34% at range of 2–36 mo.s
2003	Margara, 2003	121 ischial PUs over 15 yrs	33% over first 7 yrs (n = 57) 9% over next 8 yrs on stricter treatment protocol (n = 64)
2004	Coşkunfirat, 2004	35 gluteal PUs in 32 consecutive pts over 4 yrs	3% at mean of 13.6 mo.s
2005	Kuwahara, 2005	8 sacral PUs	38% at 1 to 4 yrs
2009	Keys, 2009	231 flaps in 139 pts over 15 yrs	36% surgical site
2009	Lee, 2009	20 ischial PUs over 8 yrs	50% surgical site, at mean 74.2 mo.

the spread of tissue damage [1, 13, 14]. These mechanical changes then lead to increased stresses in the injured area, resulting in a "snowball effect" that is difficult to halt [1]. Pathologic changes are more severe in muscle than in skin or subcutaneous tissues [67, 73], perhaps reflecting the higher metabolic demands of muscle and explaining the importance and prevalence of deep tissue injury (DTI) [25, 66, 67, 73]. PU severity is most commonly staged according to the National Pressure Ulcer Advisory Panel system, originally put forward in 1989 based on Shea's classical staging from 1975 [4, 62]. It consistently remained a 4-stage system ("Stages I-IV"), until 2007 when two additional stages were added: "Suspected Deep Tissue Injury" (DTI) and "Unstageable" [55]. The current staging system is represented in Fig. 1.

Current hypotheses about effective preventive measures generally fall into 3 broad categories: 1) weight-shifting to relieve and improve pressure distribution; 2) increasing muscle volume to provide more padding; and 3) increasing vascularity and perfusion to reduce hypoxia and accelerate recovery. These factors have reason to be correlated with each other, as well. For example, active use of a muscle immediately increases its metabolic demand and eventually increases its physical size; both factors stimulate development of its blood supply [36, 46, 58, 59]. In areas such as the buttocks where the overlying skin is supplied by musculocutaneous perforator vessels, that skin should also benefit from this improved blood supply.

Able-bodied people do not get PUs, presumably because they can voluntarily contract their muscles, thereby maintaining muscle bulk and vascularity, while shifting their weight to relieve seating pressure and so restore capillary circulation. While this should work successfully in the skin of the buttocks, it is less clear how this provides any relief in the gluteus maximus (GM) muscles when seated, where ischemic necrosis can give rise to deep ulcers independent of the overlying skin. Muscle activity increases metabolic demand while simultaneously generating hydrostatic pressure that tends to occlude intramuscular capillary beds, making it even more important not to occlude these vessels by external pressures and shear during such use.

Ever since the classic Reswick & Rogers curve was published in 1976 [60], PU risk has been recognized as proportional to the product of pressure intensity and duration [9, 16, 37, 60]. Soft tissues should therefore be able to handle higher pressures and metabolic demands when relieved by intermittent periods of low pressure during which circulation is reestablished. Able-bodied people do not get PUs, presumably because they can voluntarily contract their muscles, thereby maintaining muscle bulk and vascularity, while shifting their weight to relieve seating pressure and so restore capillary circulation. NMES could be used to activate paralyzed muscles to achieve the same beneficial effects, but the choice of target muscle(s) is not obvious. One candidate muscle is the gluteus maximus (GM), a hip
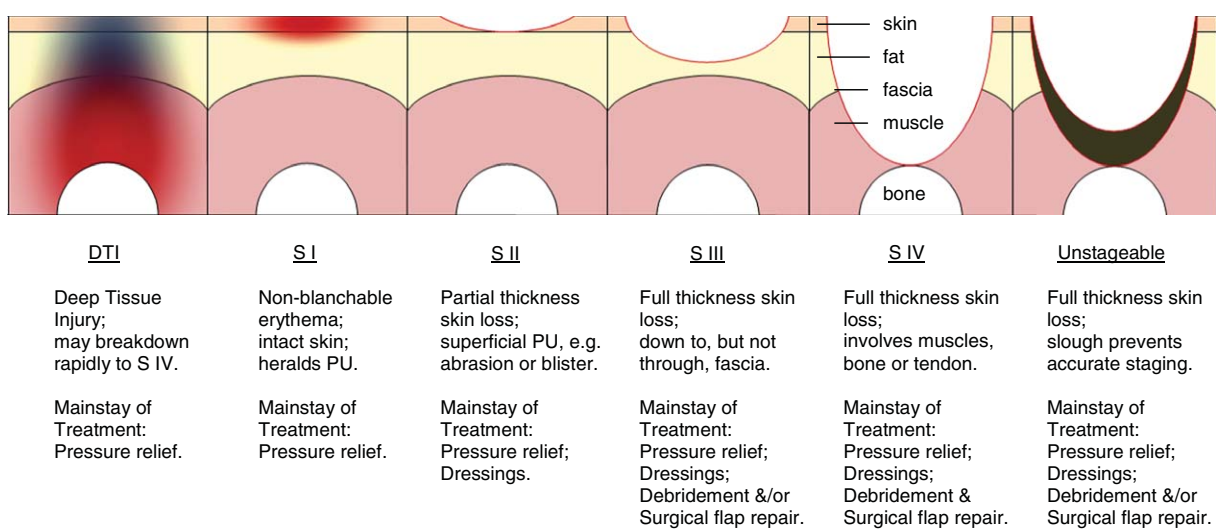

DTI	S I	S II	S III	S IV	Unstageable
Deep Tissue Injury; may breakdown rapidly to S IV.	Non-blanchable erythema; intact skin; heralds PU.	Partial thickness skin loss; superficial PU, e.g. abrasion or blister.	Full thickness skin loss; down to, but not through, fascia.	Full thickness skin loss; involves muscles, bone or tendon.	Full thickness skin loss; slough prevents accurate staging.
Mainstay of Treatment: Pressure relief.	Mainstay of Treatment: Pressure relief.	Mainstay of Treatment: Pressure relief; Dressings.	Mainstay of Treatment: Pressure relief; Dressings; Debridement &/or Surgical flap repair.	Mainstay of Treatment: Pressure relief; Dressings; Debridement & Surgical flap repair.	Mainstay of Treatment: Pressure relief; Dressings; Debridement &/or Surgical flap repair.

Fig. 1. Author's representation of the National Pressure Ulcer Advisory Panel (NPUAP) PU staging system (NPUAP 2007).

extensor, but this muscle is itself at risk of ischemic necrosis in PU prevention. Muscle activity increases metabolic demand while simultaneously generating hydrostatic pressure that tends to occlude intramuscular capillary beds. One obvious problem with using the GM muscles to unload the ischium is that there would be little or no time for circulation to be reestablished. When the muscles are passive, the weight of the body results in intramuscular pressure that occludes blood flow. When the muscles are active, the contractile force is accompanied by an increase in hydrostatic pressure that also tends to occlude blood flow. Nevertheless, some benefits of GM activation have been described empirically, as discussed below.

4. Experience with NMES

4.1. State of the art

The seminal work by Levine et al. [42], in one SCI (C4) and four able-bodied individuals, demonstrated that seated interface pressures could be redistributed by NMES of GM. Importantly, they claimed *redistributions* rather than *reductions* of ischial seating pressures. This group also promoted the significance of gluteal blood flow and soft tissue volume for PU risk [41, 43, 44].

In 1992 Ferguson's group demonstrated in 9 SCI subjects that NMES of the *quadriceps* could produce actual reductions in seated interface pressures. They proposed that these *reductions* were more appropriate than the *redistributions* that had been shown by Levine's group with NMES of GM [21]. Their protocol involved a 3 months conditioning program (30 min/day × 5+ days/week) prior to testing, and resulted in average ischial pressure reductions of 3.6 kPa (27 mmHg) and 5.9 kPa (44 mmHg) on the left & right sides respectively (from means of 10.1 kPa (76 mmHg) and 13.2 kPa (99 mmHg) respectively at rest). Some minor modifications of the subjects' wheelchairs were required, together with restraint of their lower legs. This approach also does not provide the potential local (GM) circulatory and muscle hypertrophy benefits that Levine's technique does. Further, quadriceps is primarily an extensor of the knee, but not of the hip. One of the four heads, rectus femoris, actually *flexes* the pelvis on the femur [17, 52], rather than extending it as might be desirable for unloading without having to stabilize the trunk. Finally, imbalanced stresses on the knee joints

could potentially cause damage if this technique were employed chronically. For these reasons we do not consider it the most preferable actuator for achieving all three mechanisms of action of NMES listed above (weight-shifting, increased seat muscle volume, and increased tissue health/vascularity).

More recently, other research groups have extended Levine's original case study by using different GM stimulation methodologies in larger numbers of SCI patients. Bogie, et al. [5] investigated the short-term effects of regular use of gluteal NMES in users of a semi-implanted system primarily for Functional Electrical Stimulation (FES) assisted standing and transfers. Early results reported that interface pressures in the ischial region could be significantly reduced through stimulating GM, with positive tissue health benefits ([5, 6]. In 2003 they reported on a conditioning exercise program improving tissue health in 8 patients using this same system over 8 weeks, through improved regional blood flow and interface pressure distributions [7]. Regular stimulation of GM was included as part of their exercise and standing routines. Statistically significant reductions in ischial interface pressures were reported at *post*-exercise assessments ($p < 0.01$), but the effect on ischial pressures *during stimulation* was not assessed. More recently this group appraised the long-term effects of isolated gluteal NMES for shifting weight and conditioning tissues in a single subject [8]. This case study reported the results of a 4-channel semi-implanted system used over 7 years. Absolute regions of statistically significant change in pressure were determined, but the quantitative and spatial extent of these "absolute differences" or "variations" were not provided (i.e. whether pressures actually went up or down, and by how much, in different zones during stimulation). Improvements in tissue health variables (gluteal thickness and transcutaneous O_2) were noted, and the authors predicted that daily NMES would be required to prevent disuse atrophy from recurring.

In 2006 Liu's group reported on GM activation via stimulation of the S2 sacral roots [47, 48]. They compared Functional Magnetic Stimulation (FMS) in 5 able-bodied subjects with electrical stimulation via an implanted Sacral Anterior Root Stimulator (SARS) in 5 SCI subjects. The S2 nerve roots were demonstrated to reliably activate the gluteal muscles in both cases, but simultaneous direct or reflexive activation of the hamstring (HS) hip extensors cannot be ruled out. Average peak pressures were reported for only small ($1.3 \times 1.3 = 1.6 \text{ cm}^2$) regions directly under the ischial

tuberosities (ITs), where they were found to be reduced by 20% with FMS and by 33% with SARS.

In 2007–2008 Janssen et al. reported on the benefits of GM activation through surface stimulation in 13 SCI males [30, 72]. Alternating side-to-side stimulation was compared with simultaneous bilateral stimulation. Average pressure reductions in small ($3.6 \times 3.6 = 13cm^2$) zones immediately beneath the ITs were similar for both protocols ($\sim$2.5 kPa (18.5 mmHg)).

4.2. Biomechanical considerations

One general problem in studying PUs arises from the localized and labile nature of pressure peaks. Solis et al. described an experimental model in which they elicited DTI in rats by applying constant loads of 38% of the body weight (their expected unilateral loading in seated individuals) to the quadriceps, for 2 hours, with a 3 mm diameter indenter [64]. Experimental groups received intermittent NMES via nerve-cuff electrodes during this constant pressure application. In vivo assessment of deep tissue health was performed using MRI (for detecting muscle edema and oxygenation), 24 hrs following pressure application. The authors concluded that intermittent NMES significantly reduces the amount of DTI by increasing the oxygen available to the tissue and by modifying the pressure profiles of the loaded muscles. However, because the pressure was only exerted over a very small area ($0.07cm^2$), it is likely that stimulation was in fact relieving the muscle by simply intermittently removing it from the pressure zone completely (which would not be the case with GM stimulation in seated individuals).

Solis et al. also measured the changes in GM tissue oxygenation and in surface interface pressures that resulted during GM surface stimulation in a single, able-bodied human subject. Because of limited space within the MRI scanner, muscle compression during "sitting" was simulated by adding a mass (30% of body weight) over the pelvis of the subject, who was lying supine within the scanner with hips extended rather than flexed. A $\sim$4% reduction in tissue oxygenation (from baseline) was noted during compression of the buttocks, with a $\sim$6% increase (from baseline) after GM activation. Surface pressure profiles of the loaded muscles were redistributed and the high-pressure points (over the sacrum) were reduced during surface NMES. This is consistent with the analysis of extensor moments (companion paper II, Fig. 2) [31] for

this *supine* posture, and so the findings support a mechanism for prevention of PUs in *bed-ridden* patients that we have proposed previously [33]: As GM is the dominant hip extensor when the hip is *extended*, such as during upright locomotion and when lying in bed, the potential exists for GM stimulation to extend and abduct the hip and so roll bed-ridden patients axially, which may relieve both ischial and sacral pressures when supine.

The historical emphasis on GM may have distracted from a systematic analysis of the complete musculoskeletal mechanics. Davis & Triolo's group recognized that the biarticular HS muscles extend the thigh at the hip, with minimal knee flexion [17], but asserted that GM is the strongest hip extensor when the hip is *flexed*, and that HS are optimal for hip extension when the hip and knee are *extended*. Older anatomy texts were referenced [29, 51], and GM has been widely quoted as the strongest hip extensor without regard to hip posture. See companion paper II for a more systematic study of the biomechanics of these muscles [31]. Over the past decade Bogie & Triolo et al. have advocated the use of GM stimulation for PU prevention [5–8, 74], but largely as part of more extensive FES involving other muscles too for standing and transfers (HS, vastus lateralis, erector spinae) [7].

While appropriately targeted NMES might reduce normal forces on soft tissues, it may actually tend to aggravate shear injury by repeated movement. Several researchers have attempted to qualify and quantify the relative importance of increased shear [24, 25, 45, 68]. Over the past decade groups such as Bouten's [10, 24, 25], Stekelenburg's [67, 68], and Linder-Ganz & Geffen [45] have questioned one of the most basic assumptions about PU etiology: Do muscle cells under bony prominences die due to *hypoxia and ischemia* directly, or is tissue damage predominantly a consequence of the *mechanical loading* itself? Recently Linder-Ganz & Geffen employed animal (rat) and computer models to investigate the relative effects of pressure vs. shear on capillary patency in relation to DTI [45]. Even relatively low shear strains (<10%) were found to decrease patent capillary cross-sectional area substantially (34–55%), so contributing to the effect of compressive stresses by increasing the extent of tissue ischemia. The effects of NMES on shear in the buttocks has not been considered in any of the studies of NMES for PU prevention to date, probably because it depends complexly on the mechanical actions of the muscles being activated, as well as the

patient's posture, and the shape and surface texture of the seating support and clothing. The biomechanical analysis presented in companion paper II includes information about the complete skeletal moments produced by the relevant muscles [31], which would be a necessary starting point for future analysis of their effects on shear in various seating configurations.

4.3. Interfacing technology

In addition to questions about optimal muscle targets and pathophysiologic mechanisms, the neural-electronic interfaces currently available for NMES are poorly suited for chronic use by these patients. To be attractive as a prophylactic measure in disabled patients who are already at risk, it is important that this activation be achieved with minimal daily intervention by the patient or caregivers, and minimal probability of side-effects or complications. Currently available technologies for NMES cannot meet all of these requirements, and include three basic platforms: (1) *Surface stimulation* is difficult to employ chronically because it requires precise localization of the electrodes and adjustment of stimulus parameters for each session. Repeatedly sticking large electrodes on the skin is cumbersome, and long-term practicality and patient compliance is problematic [47, 48]. Selective stimulation of the deep muscle nerves to GM and HS is difficult to achieve transcutaneously [8]. Other problems with this approach include pain and/or reflex spasms due to cutaneous stimulation, as well as pressure and irritation from the electrodes themselves, impacting skin that is often moist and already at risk for breakdown. (2) *Percutaneous leads* with intramuscular electrodes have been developed to improve selectivity and reliability of stimulation. However their placement is invasive, and patients run the risks of infection, erosion, fistulae, scarring, and lead breakage and migration. Repeated interventions may be required to address these issues. (3) *Fully implanted multichannel stimulators* with leads have also been employed, but require extensive surgery to route the leads and to place the relatively bulky stimulators (about the size of a pacemaker) [7]. These leads are also prone to infection, breakage and migration. They are probably justifiable only if they can provide functional benefits such as standing or walking.

In companion paper III [32], we present results from a clinical pilot study of a new alternative - a generic technology comprising fully implanted, miniature, wireless microstimulators that can be located directly at the site of stimulation.

5. Conclusions

NMES of the buttock muscles appears to be valuable in terms of its trophic effects, improving vascularity and soft tissue bulk. It is not clear, however, whether it can actually achieve sufficient unloading of normal forces to permit blood flow in the capillary beds of the skin and muscles. In order to prevent ischemic damage to these tissues and consequent PU formation while seated, it would seem necessary to reduce pressures (compressive stresses) periodically, *in all* contact areas, to below that sufficient to occlude blood flow in the capillary beds. Furthermore, this should be accomplished using muscles other than those whose blood flow is occluded while at rest. Because the weight of the body that must be supported is constant, NMES will be effective in meeting this requirement only if it produces intermittent, substantial shifts in the distribution of seating pressures between the buttocks and thighs.

Acknowledgement

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