

# Myoelectric and Progressive Motor Training for Phantom Limb Pain in People with Amputations During War: A Feasibility Report

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**Purpose:** Phantom limb pain (PLP) is a common condition after limb amputation which is notoriously difficult to treat. The Russian full-scale invasion of Ukraine has resulted in over 100,000 people with amputated limbs and persistent PLP. This study reports on the feasibility of implementing two novel treatment approaches, Phantom Motor Execution (PME) and Progressive Motor Training (PMT), during the Russian war on Ukraine.

**Methods:** PME and PMT follow the principle of facilitating motor training of the phantom limb and are grounded on the Stochastic Entanglement hypothesis for the pathogenesis of PLP. PME employs myoelectric pattern recognition on residual limb muscles to control virtual and augmented reality environments (mixed reality). PMT uses mixed reality to guide patients to imagine or execute predefined movements according to their evolving motor skills, and it is suitable for patients where myoelectric signals are not viable. Nineteen participants with major limb amputation were treated with PME (N=8) and PMT (N=11).

**Results:** Participants who completed 9 sessions reported a reduction of PLP greater than 50%. Participants received half of the training time per session and less sessions than reported in previous studies, yet clinically meaningful pain reductions were observed.

**Conclusion:** This study demonstrates the feasibility of implementing PME and PMI for the treatment of PLP during war time and constraint resources. Ukrainian clinicians found the technologies and treatment approaches efficient and effective at reducing PLP and have introduced them as part of their clinical practice.

**Keywords:** phantom limb pain, progressive motor training, phantom motor execution, amputations, neuropathic pain, motor imagery, motor execution, virtual reality

## Introduction

Approximately over 100,000 people have suffered major limb loss due to the Russian full-scale invasion of Ukraine since February 2022. The prevalence of PLP elsewhere has been estimated at 64%.<sup>1</sup> Although official statistics are unavailable due to ongoing conflict, anecdotal reports suggest that the incidence of PLP in Ukraine exceeds that commonly reported in the literature. Several factors may account for the higher incidence of PLP among war victims, including prolonged duration between injury, evacuation, and the final amputation procedure;<sup>2</sup> the psychological adverse factors of an ongoing war;<sup>3</sup> and unprioritized nerve treatment during amputation due to time and resource constraints. From the beginning of the Russo-Ukrainian War in 2014, and prior to the full-scale invasion, PLP had already been identified as a major difficulty in the rehabilitation of war-injured veterans.<sup>4</sup>

Treatments for PLP, ranging from surgical to plasticity-guided interventions, have been employed clinically worldwide.<sup>5</sup> Notably, pharmacological approaches serving as a pain management strategy, rather than treatment, are



often considered unsuitable as long-term solutions but indispensable in acute pain.<sup>6</sup> After failing to find effective and efficient treatments for PLP for our clinics in Ukraine, we sought to implement novel approaches that could remain feasible during wartime. We implemented Phantom Motor Execution (PME) as employed previously with positive results.<sup>7</sup> PME relies on the possibility to record myoelectric signals from muscles in the residual limb, which are used to infer motor intent in the missing (phantom) limb. The resulting phantom motor volition can then be visualized using virtual and augmented reality (VR/AR) environments, which allows for the implementation of serious gaming.<sup>8</sup> A consequence of the Stochastic Entanglement hypothesis for the pathogenesis of PLP is that re-engaging the neural resources of the affected limb would drive plastic neural changes throughout the neural axis disassociating pathologic pain processing, and this is hypothesized as the working mechanism of PME.<sup>9</sup>

A key challenge with utilizing myoelectric pattern recognition for treatment is the reliance on residual limb muscles, which are often compromised.<sup>10</sup> In addition, war injuries are often complex and require extended healing periods extending for several months, during which conventional rehabilitation cannot be provided, despite the development of PLP. In consideration of this, we implemented Progressive Motor Training (PMT) to provide timely treatment for patients in whom residual limb electromyography is not feasible.<sup>11</sup> PMT guides the patient to imagine and then execute movements shown in VR/AR environments. Previous work has shown that VR/AR guided motor imagery can achieve similar alleviation of PLP as PME using myoelectric pattern recognition.<sup>12,13</sup> As derived by the Stochastic Entanglement hypothesis, this could be explained by the larger cortical neural resources employed when imagining complex movements, which can be comparable in proportion to that required for the execution of simpler movements in which circuits in sub-cortical areas and the spinal cord are involved.<sup>9,11</sup> Ideally, most neural resources related to the affected limb should be recruited in the execution of complex movements. However, the execution of complex movements is difficult when attempted with phantom limbs that are often perceived as paralyzed.<sup>14</sup> PMT takes advantage of motor imagery to facilitate execution, thus allowing training with simple and complex movements from the first intervention.<sup>11</sup>

Here, we report on the first implementation PME and PMT under constraint resources and during war. PMT was provided in cases where PME was not feasible due to the unavailability of myoelectric signals.

## Methods

### Participants

This study was approved by the ethical committee at the National Pirogov Memorial Medical University (7/072025). Participants were treated at the Regional Pirogov Memorial Clinical Hospital and Prometei Pain Rehabilitation Center, both in Vinnytsia, Ukraine, and provided written informed consent prior treatment. Participants were older than 18 years, could read and communicate in Ukrainian, suffer from PLP, and underwent limb amputation more than three months prior treatment. We did not consider individuals with addictive disorders; severe psychiatric disorders; significant cognitive impairment due to memory problems and brain disorders.

### Phantom Motor Execution

The PME protocol consisted of 30-minute treatment sessions conducted every other day for up to 9 sessions. The technology to conduct PME and training protocol has been described extensively in prior studies.<sup>7,8,13</sup> Briefly, a training session involved placement of electrodes, recording of myoelectric signals associated with the execution of a set of predefined movements, and then training in VR and AR environments performing the recorded movements now reflected in the movement of a virtual limb (Figure 1), or to control games. The set of movements was made progressively more difficult over time according to the ability of the participant and at the discretion of the therapist.

### Progressive Motor Training

The PMT protocol consisted of 30-minute treatment sessions conducted every other day for up to 9 sessions. The guiding movements were provided in VR or AR environments as preferred by the participants (Figure 2). Participants were asked to execute a movement with their phantom limb three times. If they were unable due to feeling their phantom limb locked



**Figure 1** Example of a treatment session with Phantom Motor Execution (PME).



**Figure 2** Example of a treatment session with Progressive Motor Training (PMT).

or frozen in place, they were instructed to imagine performing the movement three times, with progression to motor execution when possible.

## Outcomes

Participants completed a pain questionnaire consisting of numeric rating scales (NRS) at baseline and after every third training session, for phantom and residual limb pain intensity, as well as PLP interference with activities of daily living (ADL) and sleep.

## Data Analysis

Data were analyzed using “R” version 4.5.1. The primary outcome is PLP severity, with a minimal clinically important within-group difference in pain reduction (50%) from baseline used to classify the treatment as successful.<sup>15,16</sup> Given the small sample size in this study, all outcomes are presented using descriptive statistics.<sup>17</sup>

## Results

Nineteen males with a median age of 37 (IQR: 30–42) were treated. All participants had undergone amputations due to trauma: 13 transfemoral, four transhumeral, one transradial, and one transtibial. All participants had previously received Mirror Therapy and medications for acute pain. At baseline, two participants were receiving Pregabalin (225 mg and 300 mg daily, respectively), while one additional participant was receiving Diclofenac (100 mg daily) as part of their ongoing analgesic management. Two participants presented with symptomatic neuromas, identified clinically during the initial assessment. In PME, four participants (50%) completed nine sessions and the other half six sessions. In PMT, six participants completed nine sessions (55%), then three and two participants completed six and three sessions, respectively. The participants were unable to complete all sessions due to transfer to other hospitals.

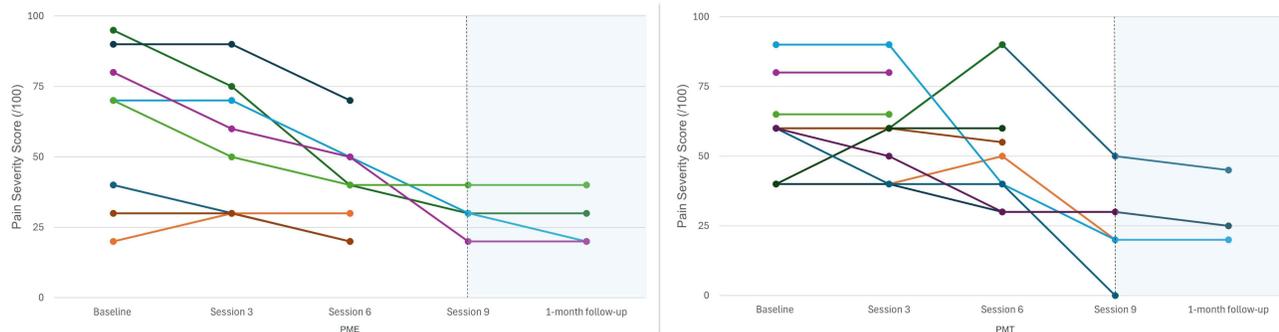
### PLP Severity

The PME group had a median baseline PLP score of 70 (IQR: 35–85), which was significantly lower after the last treatment session [30 (IQR: 25–35)] (Figure 3). Within-group difference between baseline and end of treatment scores was 40 [95% CI (8.45–71.55)]. Further improvements were seen at 1-month follow-up [25 (IQR: 20–35)].

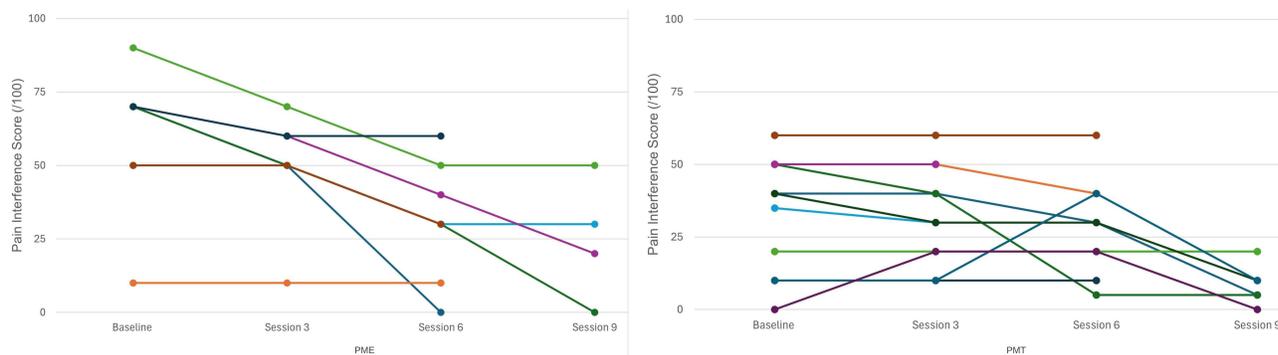
The PMT group had a median baseline PLP score of 60 (IQR: 40–65), which was significantly lower after the last treatment session [25 (IQR: 20–30)] (Figure 3). Within-group difference between baseline and end of treatment scores was 35 [95% CI (21.53–48.47)]. Further improvements were seen at 1-month follow-up [22.5 (IQR: 20–35)].

### PLP Interference with ADL

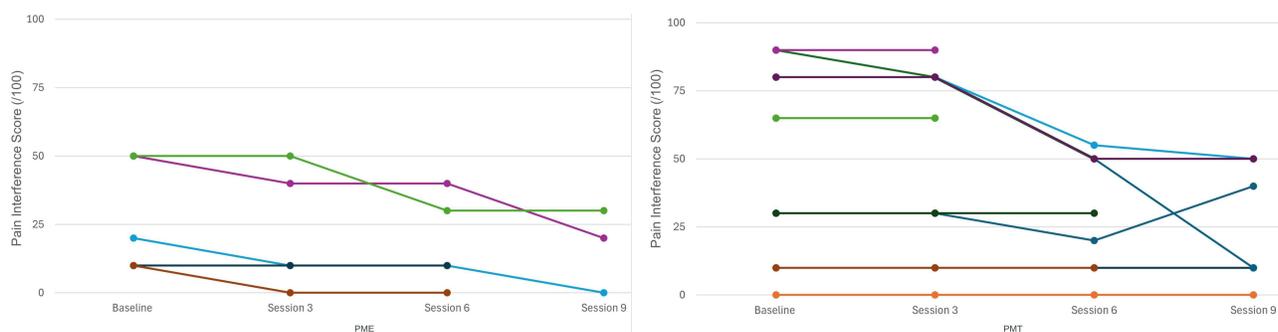
The PME group had a median baseline pain interference score of 70 (IQR: 50–70), which was significantly lower after the last treatment session [25 (IQR: 10–40)] (Figure 4). Within-group difference between baseline and end of treatment scores was 45 [95% CI (22.63–67.37)].



**Figure 3** The effect of PME and PMT on PLP severity.



**Figure 4** The effect of PME and PMT on pain interference with ADL.



**Figure 5** The effect of PME and PMT on pain interference with sleep.

The PMT group had a median baseline pain interference score of 40 (IQR: 20–50), which was significantly lower after the last treatment session [10 (IQR: 5–15)] (Figure 4). Within-group difference between baseline and end of treatment scores was 30 [95% CI (14.25–45.75)].

### PLP Interference with Sleep

The PME group had a median baseline pain interference score of 25 (IQR: 10–25), which was lower after the last treatment session [10 (IQR: 0–25)] (Figure 5). Within-group difference between baseline and end of treatment scores was 15 [95% CI (–3.04–33.04)].

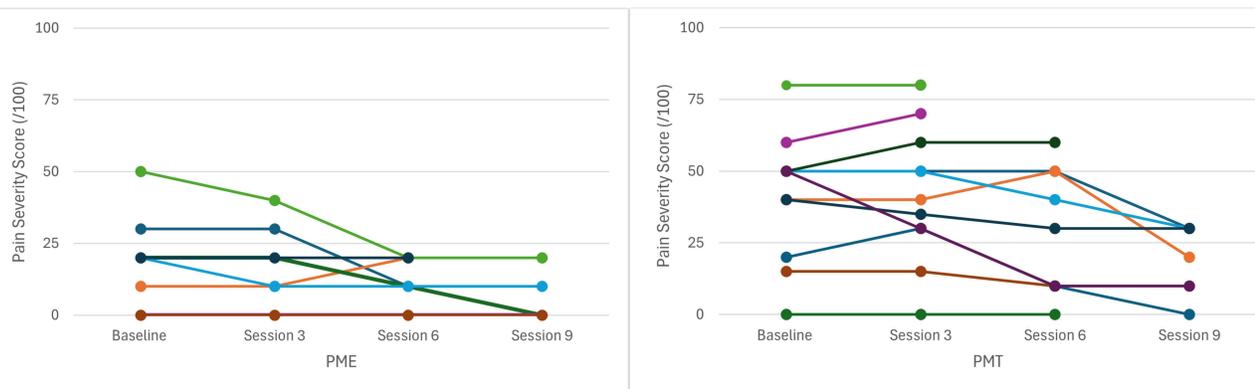
The PMT group had a median baseline pain interference score of 65 (IQR: 10–80), which was lower after the last treatment session [40 (IQR: 10–50)] (Figure 5). Within-group difference between baseline and end of treatment scores was 25 [95% CI (–15.12–65.12)].

### Medication, Neuroma Pain, and Residual Limb Pain

The two participants on Pregabalin reduced the intake from 225 mg to 150 mg (33%) and from 300 mg to 100 mg (67%) by the end of the treatment. Notably, the two participants who presented with symptomatic neuromas did not report any reduction in PLP during the intervention period. The distribution of residual limb pain (RLP) throughout the study is shown in Figure 6.

### Discussion

The current study was conducted during the war on a population that appears to show a higher incidence of PLP than previously reported. Due to current restrictions, it is not possible to conduct epidemiological studies on war casualties; however, the experience of clinicians treating these participants indicates that most, if not all, report enduring PLP. The participants in this study had been treated with Mirror Therapy and medications with unsatisfactory results. This study



**Figure 6** Distribution of RLP during PME and PMT interventions.

aimed to evaluate the feasibility of using modern treatments based on digital technologies, and with defined working mechanisms,<sup>9,11</sup> in our current, demanding clinical practice. The number of war injuries has overwhelmed the Ukrainian healthcare system, with limited resources to attend to all patients who need treatment. The use of digital technologies represents a potential solution to satisfy the growing demand for PLP treatment. Moreover, these approaches can also be used to restore function in severe motor impairments such as after stroke<sup>18</sup> or arm replantation.<sup>19</sup> Here, we extend their application to a cohort of participants with war-related amputations, demonstrating its feasibility in highly resource-constrained and unstable clinical environments.

Despite constrained resources, in this study, we found similar results as previously reported in other studies (>50% reduction of PLP),<sup>7,8,13</sup> with an important difference in that here, participants received 30 minutes of treatment per session, as opposed to 90 to 120 minutes as previously employed. The maximum number of sessions here was nine, whereas in previous work it was more than 12.<sup>7,8,13</sup> The optimal length of treatment sessions has yet to be properly studied, as well as the adequate number of treatment sessions. A rule of thumb now adopted in our clinical practice is to provide 30 to 60 minutes of treatment, and as many sessions as necessary, as long as the patient reports progress, considering a minimum of nine sessions to determine if further benefits can be achieved.

We observed a general lack of knowledge regarding PLP among participants and clinicians. Participants seemed not to be sufficiently aware of the possibility of experiencing PLP, which diminished their psychological readiness for rehabilitation. On the other hand, clinicians felt unprepared to explain and address PLP once reported by their patients. We have now learned the importance of educating both patients and clinicians on PLP and treatment options, ranging from surgical to plasticity-guided interventions. We believe educating clinicians now helps them better diagnose the sources contributing to PLP, such as the presence of painful neuromas.<sup>20</sup> Patients with complex amputations, comorbidities, and painful neuromas are unlikely to respond favorably to plasticity-guided treatments such as those employed here, if used in isolation.

A major challenge we identified was the participants' state of mind. The trauma caused by war goes beyond the physical, and addressing it comprehensively is particularly challenging in resource-constrained environments.<sup>21</sup> We could not provide psychological support during the PLP interventions, although this would have likely potentiated the therapeutic effects of the treatment. Comprehensive pain treatment remains a major challenge.

Conventional means of treating PLP, such as medication and Mirror Therapy have been ineffective at reducing the prevalence of PLP, which has remained over 60% for decades.<sup>22</sup> The lack of standardized guidelines might be a contributor to sub-optimal pain outcomes.<sup>23</sup> In this study, we found digital technologies useful to provide more standardized treatments, and we now emphasize the importance of pain science education,<sup>24</sup> which we provide to patients as soon as possible. Randomized controlled trials are unfeasible during war time but must be conducted elsewhere to validate the efficacy of the clinical protocols employed here.

The limitations of this study are derived from the resource-constrained environment in which it took place. Although the participants received other treatment such as Mirror Therapy prior to the PME or PMI interventions, no additional

control group was included in the study. A detailed characterization of PLP including quality, frequency, and duration was not investigated due to time constraints. Similarly, no in-depth or systematic psychological evaluations were conducted. Further studies are required to provide additional insights into the experience of PLP in this particular patient population.

## Conclusion

In this study, we demonstrated the feasibility of conducting PLP treatment during wartime using digital technologies to facilitate motor training. Our results were clinically significant and comparable to those previously reported, despite being in a resource-constrained environment, which limited us to less than half of the treatment exposure used in prior studies. Given the cost-effectiveness of these treatments, we have incorporated them into our clinical practice. Additionally, we found educating both patients and clinicians to be a critical factor moving forward.

## Abbreviations

PLP, phantom limb pain; PME, phantom motor execution; PMT, progressive motor training; RLP, residual limb pain.

## Data Sharing Statement

The datasets used during the current study are available from the corresponding author on reasonable request.

## Ethics Approval and Consent to Participate

This work complied with the Declaration of Helsinki and was approved by the ethical committee at the National Pirogov Memorial Medical University (7/072025), and participants provided informed consent.

## Consent for Publication

The people in [Figure 1](#) provided written informed consent for the image to be published.

## Disclosure

MBK, MB, and MOC are shareholders of NeuroRehab Technologies OÜ. MB and MOC are inventors of a patent related to PMT. MB has a patent EP4291139A4 pending to NEUROREHAB TECHNOLOGIES OÜ, a patent US20240082533A1 pending to NEUROREHAB TECHNOLOGIES OÜ, a patent JP2024507172A pending to NEUROREHAB TECHNOLOGIES OÜ, a patent AU2022218905A1 pending to NEUROREHAB TECHNOLOGIES OÜ, a patent CN116829105A pending to NEUROREHAB TECHNOLOGIES OÜ, a patent KR20230146024A pending to NEUROREHAB TECHNOLOGIES OÜ, a patent PCT/EP2025/084676 pending to NEUROREHAB TECHNOLOGIES OÜ. MOC reports grants from Promobilia Foundation, during the conduct of the study; In addition, MOC has a patent 22753069.8 pending to NeuroRehab Technologies, a patent PCT/EP2025/084676 pending to NeuroRehab Technologies. The authors report no other conflicts of interest in this work.

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