2025 International Conference On Rehabilitation Robotics (ICORR)
May 12-16, 2025. Chicago, IL, USA

Evaluating Cognitive Workload with the Auditory Stroop Task While Using a Lower Limb Prosthesis: A Feasibility Study

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2025 International Conference On Rehabilitation Robotics (ICORR) | 979-8-3503-8068-2/25/$31.00 ©2025 IEEE | DOI: 10.1109/ICORR66766.2025.11062936

***Abstract*— This study explored the feasibility of using the auditory Stroop task to assess cognitive workload in a dual-task paradigm. Performance on two tasks—counting backward by 3 and the auditory Stroop task—was measured across two conditions: participants' own passive device and a direct EMG-controlled (dEMG) device. Results based on individual participants' data indicated that the auditory Stroop task effectively captured more consistent dual-task costs under cognitively demanding conditions, whereas the backward counting task exhibited minimal and less consistent performance deterioration. Participant interviews suggested that the backward counting task might be less sensitive to workload because participants could use strategies, while no strategies were reported for the auditory Stroop task. Although the findings are promising, this study was limited by a small sample size, which precluded statistical analysis. Future research should involve larger samples to confirm the auditory Stroop task's validity for measuring cognitive workload while using a lower limb prosthesis.**

Keywords*— cognitive workload, dual-task paradigm, evaluation methods

I. INTRODUCTION

Like other rehabilitation robotics, lower limb prosthetics are using increasingly sophisticated mechanisms, such as direct electromyography control and finite state machine-based impedance control, to improve motor function for amputees. There is encouraging evidence of these advanced control methods replicating the natural limb control mechanism and increasing the sense of agency [1]. However, one of the significant challenges that comes with these newer prosthetic control methods is that it demands substantial cognitive resources to use them (for a review, see [2]). This poses difficulty as prosthesis wearers must consciously monitor and adjust their movements to ensure stability, especially during complex tasks like walking on uneven surfaces or navigating stairs [3, 4]. The increased cognitive load can lead to fatigue and impaired walking mechanics [5]. Studies have shown that attention and cognitive efforts are crucial for prosthesis users to manage both their movements and the external environment [4]. As a result, developing advanced lower limb prostheses that are easy, safe, and comfortable to use requires a precise way to measure cognitive workload during walking. Despite this strong need, there is currently limited methods for a precise, real-time, and continuous measure of cognitive workload associated with lower limb prosthesis usage.

Existing methods for quantifying cognitive workload during walking with a lower limb prosthesis face various challenges, such as not being real-time or precise, or facing high equipment and data processing barriers. Specifically, questionnaire measures such as the NASA-TLX [6] are valid and easy to use but can only be used to capture overall workload at the end of a session or condition. Physiological measures, like eye tracking and brain activity monitoring [7, 8], offer more precision but require significant investment in equipment setup and extensive data processing (i.e., high capability but also high equipment demand). The dual-task paradigm, which involves having participants perform a secondary task while simultaneously walking. This approach assesses the cognitive workload of walking by analyzing how well participants can manage both tasks simultaneously. It provides an alternative that balances the need for accurate cognitive workload measurement with the constraints of equipment feasibility. However, it still poses challenges in terms of selecting appropriate secondary tasks that effectively simulate real-world demands. Therefore, a balanced task is needed to achieve a better compromise between measurement capability and equipment demand.

This study was supported by the National Institutes of Health (NIH award # 1R01HD110519 - 01A1 and 02S1) to HH, JF and ML

In this paper, we discuss the literature background, including relevant methods and challenges in measuring cognitive workload using the dual-task paradigm in the context of lower limb prosthesis use. We then introduce auditory Stroop task that strikes a balance between equipment demand and measurement capability, presenting preliminary evidence of its effectiveness through data from three pilot amputee participants.

A. *Dual-Task Paradigm*

The dual-task paradigm is a commonly used approach to assess cognitive workload. This method involves having participants perform two tasks simultaneously, with one being the primary task, such as “time up and go” test (TUG), and the other as secondary cognitive task, such as solving arithmetic problems [9]. Depending on the instruction of task prioritization (i.e., ensure good performance on either the primary or the secondary task), the extent to which performance on the other task deteriorates indicates a dual-task cost. Studies have used dual-task cost to reveal cognitive workload with prosthesis use. For example, Shaw et al. [10] found that transfemoral amputees showed reduced performance on a visual secondary task while walking compared to sitting, whereas those with transtibial amputations displayed consistent secondary task performance in both seated and walking conditions. This suggests that walking with a prosthesis places greater cognitive workload on individuals with more proximal amputations.

While dual-task paradigms are widely used in previous studies, the selection of an appropriate secondary task requires careful consideration. For instance, visual secondary tasks used to evaluate cognitive workload can interfere with walking, limiting their feasibility to controlled environments like treadmill-based simulations [10]. Therefore, it is essential to identify a secondary task that enables precise measurement and continuous monitoring during walking.

B. *A Clinical Task: Counting Backward*

Counting backward is frequently used as a secondary task in the dual-task paradigm to introduce an additional cognitive demands because of its simplicity and capacity to challenge cognitive resources [11, 12]. In this task, participants are typically given a starting number and are asked to keep reporting the next numbers by continuously subtracting another number. For example, starting with 89 and counting backward by 3 would lead to answers 82, 79, 76, 73, 70, 67, and so on. This task involves cognitive components such as attention and working memory, and it is favored in clinical settings as a secondary task to identify risks in mobility and walking safety. For example, Vance et al. [13] found that adding counting backward to TUG improved the identification of fall risk in people with Parkinson's disease. In the context of amputation rehabilitation, Frengopoulos et al. [14] found that using counting backward as a secondary task affected amputees’ walking performance similarly, regardless of their etiology, levels of amputation and time with the prosthesis.

Despite its usefulness, using counting backward to assess cognitive workload has limitations that impact measurement accuracy and precision. Potential confounding variables, such as individual math ability and stress-related math anxiety, could pose problems. For low performance individuals, it may be difficult to differentiate due to the floor effect. Given the participant has already performing poorly at baseline, there is little room to show the effect of increasing primary task demand leading to even worse performance. Furthermore, final counts of correct responses instead of response times are usually used as the performance measure for convenience, leading to issues of missing information about the workload dynamics. Given these limitations, it is perhaps not surprising that in some studies (e.g., [9]), no differential cognitive workloads were reflected in the counting backward task, even when participants perceived significantly different cognitive burdens. This suggests the possible lack of sensitivity of the task for evaluating the cognitive workload associated with different lower limb prosthesis technologies. As such, while counting backward is convenient, its limitations suggest the need for alternative or supplementary methods to provide a more precise and continuous assessment.

C. *An Alternative Lab-Based Task: Auditory Stroop*

The auditory stroop task presents a promising alternative to the counting backward task for assessing cognitive workload as the secondary task in dual-task walking. The auditory Stroop task requires participants to process conflicting auditory information, such as hearing the word "high" spoken in a low pitch and responding based on the pitch rather than the word’s meaning [15]. The cognitive demand of resolving such conflicts taps into attention and executive function, making it a suitable concurrent task with walking [16]. In the context of prosthesis use, the auditory Stroop task has been shown to cause wider steps in participants with transfemoral amputation using microprocessor knees [17], suggesting increased cognitive workload associated with the dual-task condition as compared to the single task (i.e., walking-only) condition. Compared to counting backward, the auditory Stroop task minimizes potential impact from individual variability related to math skills. It is also highly relevant to daily tasks that require resolving conflicts among perceptual information. Furthermore, it maintains a predetermined timing of trials so sampling rate of response time and accuracy data can remain consistent throughout the walking task, instead of potential loss of data sample due to strategy use when performing the counting backward task (e.g., participant stopped doing the counting due to difficulty in counting or walking).

While existing evidence and considerations point to the promise of the auditory Stroop task, much remains to be examined. For example, to use this task to compare different prosthesis technologies, the task prioritization instruction needs to emphasize the walking performance being the priority. Then by observing participants performance on the Stroop task, we can quantify the cognitive workload associated with each prosthesis technology. Second, feasibility studies are needed to find out a proper setting of the auditory Stroop task, such as the pace of trials, to ensure the task effectively captures cognitive workload under different walking conditions. Third, the psychometric properties, such as sensitivity, need to be ensured. In the case of using auditory Stroop task to evaluate cognitive workload, sensitivity indicates how well the task can accurately capture changes in cognitive workload [18]. By comparing the results of the auditory Stroop task under different imposed workload conditions, we can evaluate how sensitive the task detects the cognitive changes across varying conditions. Additionally, observations from prosthesis wearers are essential to validate the findings. These considerations call for expanded investigation of the feasibility and effectiveness of the auditory Stroop task as a cognitive workload measure in the dual-task paradigm.

D. The Current Study

The study aimed to explore the feasibility of using the auditory Stroop task as a tool to assess cognitive workload in a dual-task paradigm. Specifically, participants completed two tasks—counting backward by 3 and the auditory Stroop task—while operating two devices: their own passive device and a direct EMG-controlled (dEMG) device. In addition to task performance, interviews were conducted to gain qualitative insights into participants' experiences.

II. METHODS

A. Participants

Three participants with transtibial amputations were recruited for this study (1 male, 2 females). Participants' age ranged from 29 to 70 years, the height ranged from 1.64 meters to 1.80 meters, and years of amputation were 5 to 18 years. The reason for amputation was edema, cancer, or trauma. All participants were recruited from the community.

B. Measures

1) Timed Up and Go (TUG)

Participants began the task by standing up from a chair, then walked 3 meters to a line marked on the floor, turned around, walked back, and sat down. They were instructed to walk as quickly and safely as possible. The time from standing up to sitting down was recorded using a stopwatch.

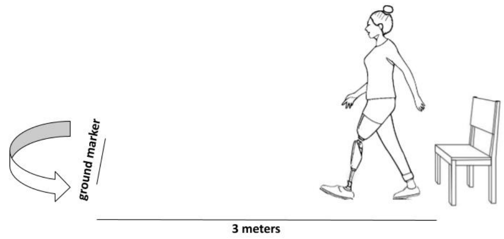

Fig. 1. Timed up and go setup.

2) Counting Backward by 3

Participants were instructed to count backward by threes from a randomly selected number. In the single-task condition, participants counted backward for 30 seconds. In dual-task condition, participants counted backward during the duration of the TUG. The number of correct responses were recorded and used to calculate accuracy. Counting speed was determined by dividing the total number of responses by the counting duration.

3) Auditory Stroop Task

The auditory Stroop task was programmed using OpenSesame [19]. Each trial began with a 200-millisecond break, followed by a 350-millisecond auditory beep, then a 150-millisecond interval. Participants then heard the word "high" or "low" spoken in either a high or low pitch. Then participants heard the word "high" or "low" spoken in either a high pitch or a low pitch. Using a clicker with up and down arrows, participants responded by pressing the up arrow for high-pitch sounds and the down arrow for low-pitch sounds.

Trials were organized into blocks. Each block consisted of four trials with unique combinations of words and pitches, presented in a random order. In the single task condition, participants completed four blocks, resulting in a total of 16 trials. In the dual-task condition, participants were asked to respond while performing the TUG. Therefore, the number of completed trials varied based on their TUG performance. The reaction time for each trial and the number of correct answers were recorded as measures of performance.

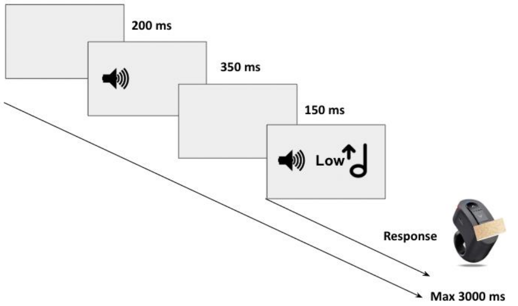

Fig. 2. Auditory Stroop task. The condition shown in the figure presents the word *low* in a high pitch, and the participant needed to respond by pressing the upper arrow on the clicker.

4) Dual-Task Cost

Participants were instructed to primarily focus on walking. Dual-task cost was defined as the percent change in performance relative to an individual's single-task performance [20]. A greater dual-task cost implicates greater performance deterioration under dual-task conditions. To reflect the cost in accuracy for the counting backward and auditory Stroop task, the dual-task cost was calculated as follows (1):

$$\frac{(single\_task - dual\_task\ )}{single\_task} * 100\% \qquad (1)$$

For speed and response time (2), dual-task cost was calculated as follows:

$$\frac{(dual\_task - single\_task)}{single\_task} * 100\% \qquad (2)$$

C. Procedure

The study protocol was approved by the Institutional Review Board of the university, and written informed consent was obtained from each amputee participant. The study was conducted as part of a larger investigation to understand the effects of a direct EMG-controlled (dEMG) powered prosthetic ankle compared to their prescribed passive prosthesis. Participants underwent performance evaluations through a series of clinical, cognitive, and biomechanical assessments using both their passive device and the dEMG device. Evaluations for the passive and dEMG devices were conducted on separate days. The reason for including both passive and dEMG devices is to examine measurement sensitivity by comparing the two different cognitive measures. Patients are known to experience difficulties using dEMG devices without prior exposure [21]. If the measurement can detect these difficulties, it would demonstrate good sensitivity.

During the cognitive assessments, participants were evaluated on their performance in the TUG, counting backward by 3, and the auditory Stroop task. They also completed dual-task conditions, in which they performed the TUG concurrently with the counting backward or the auditory Stroop task. For all dual-task conditions, participants were asked to prioritize their focus on walking. Participants first practiced the TUG, followed by two trials to assess their performance. They then practiced counting backward by 3 and completed a 30-second counting task only while sitting as the baseline. Afterward, participants performed two trials of counting backward by 3 while simultaneously completing the TUG. After a brief break, participants were asked to practice and then perform the auditory Stroop task only while sitting, which was used as the baseline. Next, they practiced and completed two dual-task trials, combining the TUG with the Stroop task.

III. RESULTS

Since each participant performed every task twice, the best performance was selected for analysis. For the cognitive tasks, the trial with the highest accuracy was chosen. If two trials had the same accuracy, the trial with the faster reaction time was selected.

A. *TUG*

1) Participant 1

For passive device, the TUG time was 17.50 seconds; with counting it was 23.00 seconds; and with Stroop was 20.20 seconds.

For dEMG device, the TUG time was 34.34 seconds When performed with counting, the TUG time was 33.00 seconds, and when combined with the auditory Stroop task, the time was 31.28 seconds.

2) Participant 2

Using the passive device, the TUG completion time was 7.95 seconds. With counting backward, the TUG time increased to 13.80 seconds. With the auditory Stroop task, the TUG time was 11.14 seconds.

With the dEMG device, the TUG time was 11.98 seconds. When performed with the counting backward task, the TUG time was 15.30 seconds, and with the auditory Stroop task, it was 12.55 seconds.

3) Participant 3

For the passive device, the TUG time was 9.78 seconds. With counting backward, the TUG time increased to 10.89 seconds. When combined with the auditory Stroop task, the TUG time was 11.96 seconds.

For the dEMG device, the TUG time was 14.08 seconds. With counting, the TUG time was 13.32 seconds, and with the auditory Stroop task, the TUG time was 14.07 seconds.

In summary, the pattern was consistent across all three participants, with both the passive and dEMG devices showing that walking speed was impacted by the dual-task conditions. Using dEMG device took longer than using their own passive device to walk (Fig. 3, upper panels).

B. *Counting Backward by 3*

1) Participant 1

For passive device, the baseline accuracy was 89% (8/9) and the counting speed was 3.33 seconds per number. When performed with the TUG, the accuracy was 100% (9/9) and the speed was 2.78 seconds per number. The dual-task cost of accuracy was -0.12, and the cost of speed was -0.17.

dEMG baseline showed a 100% accuracy (11/11) with a counting speed of 2.73 seconds per number. When performing with the TUG, this participant had 100% accuracy (7/7) and the speed was 4.71 seconds per number. The dual-task cost was 0% on accuracy and 73% on speed.

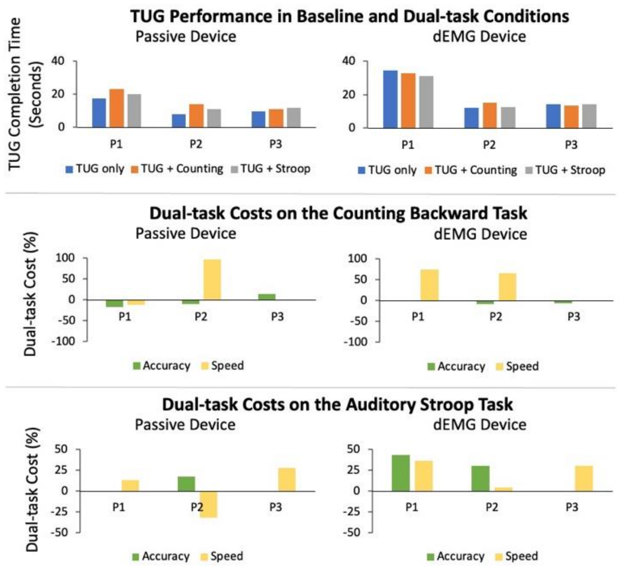

Fig 3. Performance on the Timed Up and Go (TUG) task and dual-task costs on the counting backward task and the auditory Stroop task from each of the three participants (P1, P2, P3) when wearing their own passive devices or a dEMG device. The upper panels show participants' TUG task completion time in the basline (TUG only) and dual-task conditions (TUG + Counting, TUG + Stroop). The middle panels show the dual-task costs (%) on the counting backward task. The lower panels show the dual-task costs (%) on the auditory Stroop task. A positive dual-task cost suggests the dual-task having a lower accuracy or taking longer to complete than the single task. Opposite directions of costs on speed and accuracy suggests a speed-accuracy trade-off (e.g., P33 on the counting backward task for both devices, and on the auditory Stroop task for the passive device). A greater and positive dual-task cost suggests an overall more demanding task condition (e.g., the dEMG device poses higher demand than the passive device for P1 as shown on the auditory Stroop task). Fewer negative costs and more consistent cost patterns across participants comparing the passive and dEMG devices suggest higher criterion validity and external validity of a measure. In general, based on this preliminary data from three participants, the auditory Stroop task presents more consistent and meaningful dual-task costs.

2) Participant 2

Using passive device, participant counted 11 numbers in 30 seconds with 1 error at the baseline. Accuracy was 91%. On average, the counting speed was 2.72 seconds per number. In the dual-task condition, participant counted 3 numbers with no error. Accuracy was 100% with a counting speed of 5.33 seconds per number. The dual-task cost was -10% for accuracy and 96% for speed, meaning that this participant had higher accuracy but slower speed in the dual-task condition as compared to the baseline.

Using dEMG, participants counted 13 numbers in 30 seconds and had 1 error at the baseline. Accuracy was 92% with a speed of 2.31 seconds per number. In the dual-task condition, the participant counted 4 numbers with no error. Accuracy was 100%. The counting speed was 3.83 seconds per number. The dual-task cost was -9% for accuracy and 65% for speed.

3) *Participant 3*

In passive device, baseline accuracy was 100% for the 19 total counted numbers (19/19). Counting speed was 1.58 seconds per number. In the dual-task condition, this participant counted 7 numbers with 1 error (i.e., accuracy was 86%) with a speed of 1.56 seconds per number. The dual-task cost was 14% for accuracy and -1% for speed.

For dEMG device, the baseline accuracy for counting was 94% (17/18). The speed was 1.67 seconds per number. In the dual-task condition, this participant had 100% accuracy (i.e., all correct for the 8 total counted numbers), and a speed of 1.66 numbers per second. The dual-task cost was -6% for accuracy and -1% for speed.

In summary, the dual task costs for accuracy and speed varied across participants. Only one participant showed meaningful dual-task cost in accuracy, and two participants showed dual-task cost in speed. Many results showed improved performance under the dual-task conditions (Fig. 3, middle panels), suggesting weak sensitivity and measurement stability of this task.

C. *Auditory Stroop Task*

1) *Participant 1*

For passive device, the baseline accuracy was 50%, and the response time was 780 milliseconds. With TUG, the accuracy was 50% and response time was 883 milliseconds Therefore, the dual-task cost was 0% for accuracy and 13% for speed.

For dEMG device, of the baseline accuracy was 70% with a response time of 1219 milliseconds. In the dual-task condition, the accuracy dropped to 40% and the response time increased to 1651 milliseconds. Therefore, the dual-task cost was 43% for accuracy and 36% for speed.

2) *Participant 2*

When using the passive device, on the baseline, the participant had 100% accuracy and an average response time of 707 milliseconds. When performed with the TUG, the accuracy dropped to 83.33%, although with a shorter average response time of 484 milliseconds. The dual-task cost was 17% for accuracy and -32% for speed.

Using dEMG device, on the baseline, participant had an accuracy of 95% and an average response time of 696 milliseconds. When performing with the TUG, participant had an accuracy of 66.67% and average response time of 725 milliseconds. The dual-task cost was 30% for accuracy and 4% for speed.

3) *Participant 3*

In the baseline condition using the passive device, the participant was 100% accurate with 590 milliseconds response time. In the dual-task condition, it was 100% accuracy with 758 milliseconds response time. The dual-task cost was 0% for accuracy and 28% for speed.

dEMG baseline showed 100% accuracy and 665 milliseconds response time. In the dual-task condition, the participant had 100% accuracy and 864 milliseconds response time. The dual-task cost was 0% for accuracy and 30% for speed.

In summary, the results showed dual-task costs in both response time and accuracy, except one participant had faster responses when using the passive device as compared to baseline. The general patterns across the three participants also suggest consistently greater dual-task costs when using the dEMG device compared to the passive device (Fig. 3, lower panels). Overall, the Stroop task data captured consistent and meaningful dual-task costs.

D. *Interview*

Participants were asked to reflect on their experience with counting backward and auditory Stroop task, including the strategy they used, as well as the challenges and the difficulties they encountered.

For the strategies used during the tests, all three participants reported using strategies to assist with counting backward by 3. Two participants described using mental strategies to identify numerical patterns. For example, participant 3 explained, *"when we were counting backward from three, if we went down ten numbers, we would be hitting the same numbers ... I was just trying to remember that."* Similarly, participant 1 noted, *"I've tried not to practice, but I'm getting a pattern in my head now."* Participant 2 explicitly recalled slowing down the pace and using fingers to aid in counting backward. In contrast, no participant reported any strategies used in the auditory Stroop task.

Regarding difficulties and challenges, participants 2 and 3 identified the mathematical aspect of the counting backward as particularly demanding, noting it was more challenging than the auditory Stroop task. Both participants attributed this to their mathematical abilities. For example, participant 2 mentioned, *"Maybe I'm not good at numbers, and it was all in your head". Similarly,* participant 3 stated, *"Numbers are not my thing ... I had to think a lot more [than the auditory Stroop task] while I was doing it."* Participant 1 found the auditory Stroop task was more difficult than counting backward, remarking, "*I could argue with the voices sometimes.*" In addition to the cognitive demands, participants 1 and 3 pointed out issues with the clicker, especially when managing other physical demands. Participant 1 stated, "*The clicker is the most frustrating thing, because you're holding on to the walker and holding on [to it] and having to push a button at the same time.*"

IV. DISCUSSION

The findings of the current study provide preliminary evidence that the auditory Stroop task could potentially become a valuable tool for measuring cognitive workload in a dual-task paradigm. Compared to the counting backward task, the auditory Stroop task demonstrated a consistent pattern of capturing greater dual-task costs under more cognitively demanding conditions (i.e., using the dEMG device). In contrast, performance in the counting backward task did not show much deterioration during dual-task performance and the patterns were quite inconsistent across participants when comparing the passive and the dEMG devices. This aligns with previous research [9], which suggests that cognitive workload may not be effectively reflected in the counting backward task. While counting backward has proven to be an effective task for adding load in clinical assessments of mobility and safety, preliminary results from the current study suggest it may not be the most suitable method for evaluating cognitive workload for prosthetic technologies. Instead, the auditory Stroop task appears to be a more promising alternative.

Interviews further supported that as participants reported employing strategies by identifying patterns while performing the backward counting task, which may have contributed to its insensitivity in reflecting changing cognitive workload. For future studies, the setup of the auditory Stroop task can be enhanced. In the current study, participants used a presentation clicker to respond, and all participants reported that the clicker made the task more challenging. Addressing this usability issue may improve the task's effectiveness and participant experience.

As an initial feasibility study to explore the use of the auditory Stroop task in assessing cognitive workload with the dEMG device, the findings are promising. However, a key limitation of this study is its small sample size even though the participants were amputees, which precluded the possibility of conducting statistical analyses. Future research should address this limitation by incorporating a larger sample size to enable statistical testing.

ACKNOWLEDGMENT

The authors would like to thank Avery Murray, Austin Mituniewicz, Brendan Driscoll, and Pinar Onal from North Carolina State University, as well as Derek Frankena from Atlantic P&O for their assistance with the preparation and data collection for this study.

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