

IC22: Dynamic Wheeled Mobility--Next Chapter in the Ultralight Evolution

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The prevalence of upper limb pain in full-time manual wheelchair users living with SCI is estimated to be anywhere from 30-70%. For those who rely on an ultralight wheelchair for their day-to-day function, the consequences can be significant and will impact more than just their mobility. Since they were published in 2005, the Clinical Practice Guidelines for Preservation of Upper Limb Function Following Spinal Cord Injury (CPG's) have served as a valuable evidence-based resource for clinicians and seating/wheeled mobility professionals who work with the SCI population. 1 The recommendations related to wheelchair use are based on extensive research that has examined the effects of the wheelchair's configuration and the user's propulsion technique on upper limb function. The recommendations focus on three general areas: Ergonomics, Equipment Selection, and Training. Those having the greatest relevance to the ultralight manual wheelchair are summarized in Table 1.

Table 1 - Recommendations in the CPG's for Preservation of Upper Limb Function following SCI

Area	Number	Recommendation
Ergonomics	3	Minimize the Frequency of repetitive upper limb tasks.
	4	Minimize the Forces needed to complete upper limb tasks.
	5	Minimize Extreme/Potentially Injurious Positions (e.g. Avoid having to position the hand above the shoulder or extreme shoulder internal rotation & abduction).
Equipment Selection & Training	7	Provide manual wheelchair users with SCI a high-strength, fully customizable manual wheelchair made of the lightest possible material.
	8	Adjust the rear axle as far forward as possible without compromising stability.
	9	Position the rear axle so when the hand is at the top dead-center of the pushrim, the angle between the upper arm and forearm is between 100-120°.
	10	Educate the patient to use long, smooth strokes that limit high impacts on the pushrim. Allow the hand to drift down naturally below the pushrim.

	11	Promote an appropriate seated posture and stabilization relative to balance and stability needs
	13	Provide Seat Elevation or possibly a standing position to individuals with SCI who use power wheelchairs and have arm function.
	15	Instruct individuals who complete independent transfers to perform level transfers when possible, avoid positions of impingement, avoid placing either hand on a flat surface whenever possible, and vary the technique used & arm that leads.

The CPG's provide a foundation for evidenced-based practice and some basic guidance on how to configure an ultralight wheelchair and educate its user. However, they are also a reflection of the mobility products that were available at the time they were published. This paper will challenge seating/wheeled mobility professionals, researchers, and custom mobility equipment manufacturers to objectively evaluate the current state of the ultralight manual wheelchair and its ability to preserve upper limb function in the full time user. As part of this process, we believe there are two key questions that need to be answered with respect to the status quo:

1. Is our current best practice of providing users with a single static configuration that has been optimized for steady state propulsion on smooth level surfaces the most effective way to implement the upper limb CPG's?
2. If the primary design objective of tomorrow's models is to provide the absolute lightest weight possible, will tomorrow's designs really be any more effective in preventing upper limb pain and overuse?

It is the author's contention that the answers to both of these questions is "No". We believe that the ultralight's role in preventing upper limb pain and overuse has been unnecessarily limited by a self-imposed assumption that a wheelchair's configuration has to be static. Few have questioned this assumption. As a result, our efforts over the past 10 years have led to a better understanding of the problem, but few innovations in terms of ultralight designs. We believe that innovative solutions are possible, but will be unlikely unless we adopt a different approach to ultralight wheelchair configuration. We suggest an approach that we call "Dynamic Wheeled Mobility".

Dynamic Wheeled Mobility (DWM) is an alternative to traditional ultralight configuration that combines dynamic reconfiguration with recently introduced add-on components to provide users with the ability to quickly change the base configuration of their wheelchair for improved usability in multiple environments and activities. Since the CPG's were published, a number of aftermarket add on products have been introduced which can allow today's designs to be much more effective implementing the CPG's when the ultralight is used in the community. If future designs allow users to dynamically reconfigure key aspects of their seating, it would be possible for the ultralight to implement the upper limb CPG's in very different and highly effective ways than is currently the case. In order to appreciate this potential, it is necessary to describe the limited role that today's ultralight plays in our ability to implement the CPG's.

The individual recommendations in the CPG's that are related to manual wheelchair configuration may seem to be fairly unambiguous and easily understood. The ergonomic recommendations emphasize the need to minimize frequency, forces, and extreme joint positions during propulsion. Equipment selection recommendations say to provide an ultralight configured so that the rear axle is located as far forward as possible with a seat height that provides a 100-120° elbow angle when the hand is at the top dead center of the pushrim. For maximum benefit, the training recommendations say to educate the user to limit impacts against the pushrim, use long semi-circular push strokes during the propulsion phase, and keep the hand below the pushrim during the recovery phase. When these recommendations are implemented successfully, we will have provided the user with a custom wheelchair that can be efficiently self-propelled in the environment where it will be used the most. While it may also provide the user with a supportive resting posture and good distribution of pressure, it will be far from effective in its ability to provide good usability in all routinely encountered environments and essential activities. Whenever the ultralight's usability is suboptimal in a routine context, the user will almost always be subjected to greater upper limb forces, more repetitions, and/or more extreme joint positions. In fact, the forces and joint positions that are typically encountered in these secondary contexts are oftentimes much greater than those experienced during level propulsion. If our true intent is to implement the CPG's in as many contexts as possible, it becomes imperative that we optimize usability in every routine context--not just propulsion.

The problem with conventional designs is that when we strictly adhere to the current CPG's for configuring an ultralight manual wheelchair, we will have optimized it in just one of the many contexts that are associated with full time manual wheelchair use. This one dimensional implementation is not a limitation of the CPG's, per se, it is a limitation imposed by the static nature of the ultralight's configuration. The intent of DWM is not to reject the CPG's. Rather, it attempts to implement them in new and effective ways using dynamic reconfiguration. When an ultralight is designed around this concept, the optimal configuration for propulsion across smooth level surfaces becomes the "base configuration". In other words, the base configuration becomes the starting point from which to implement the CPG's--not the end result of having implemented them!

The Grass Roots Effort to Go Over Grass With Less Effort and Win the Uphill Battle

The shortcomings of a static configuration have not been lost on a population of end users with SCI--many of whom may feel that their wheelchair poses a greater barrier to participation than their actual paralysis. 2 Many full time ultralight users are choosing to improve the usability of their ultralight in additional contexts by purchasing one or more aftermarket add on products. Typically, these products are designed to reduce rolling resistance across rough or irregular terrain, add stability by increasing the effective wheelbase, provide a mechanical alternative to pushrim propulsion, or provide an external source of power. Many products provide a combination of these attributes. Products that are consistent with DWM principles are those that can be used only when needed, are easily installed or removed from the wheelchair, and do not require significant

changes to the wheelchair's base configuration in order to use. These products significantly reduce, if not eliminate, the high amounts of upper extremity strain that are normally experienced when attempting to self-propel an ultralight in the community. That fact that many are being purchased by end users when they are not reimbursed provides some testament to their perceived value. It should also come as no surprise that many of these products were developed by individuals who use ultralight wheelchairs themselves.

While aftermarket add on products represent a significant development that allow many of today's designs to implement the CPG's in other environments, they do not address three very significant contexts where the static configuration on conventional designs makes the ultralight ineffective in preserving upper limb function.

The 800 Lb. Gorillas: Transfers, Inclines, and Functional Reach

The research suggests that long-term wheelchair users report some of the highest levels of pain during transfers, when ascending ramps, or while reaching overhead. 3 Although this has been known for some time, conventional ultralight designs continue to be ineffective in their ability to minimize forces or reduce the need to use extreme joint positions in these very critical contexts associated with full time use.

During the typical sit pivot transfer, the upper extremities must support 70-80% of the user's total body weight, and the average user may transfer as often as 14-18 times per day. Few would dispute that specific aspects of an ultralight's configuration have a direct effect on the quality of an individual's transfer. The configuration of an ultralight will have a direct effect on height discrepancies, rear wheel clearance, the size of the transfer gap, and will largely dictate the user's positioning at the time they initiate their transfer. Despite this knowledge, nearly all of the transfer research to date has considered these factors to be nothing more than control variables. 4, 5, 6, 7 Why is this the case? If the user is unable to change these things while they are in their wheelchair, there is no point in studying them. What if the ultralight provided the ability for the user to easily change their configuration to make transfers easier?.

Unless one has actually tried to self-propel an ultralight up the types of inclines that the full time user routinely encounters, it is difficult to appreciate how much upper extremity strain can be involved. The ADA standard for a new building is 4.8°, but the standard for an existing building is 7.1°, and some minivan ramps can be as steep as 10°. Numerous studies have found that it takes more than twice the force to ascend a 5-7° incline than is required for level propulsion. A portion of full time users will be unable to successfully propel up a 7° slope. Those who are able to negotiate this type of incline will need to lean forward, resort to an arc pattern of propulsion, and will have a very brief recovery phase between push strokes. 8, 9,10, 11 Could one of the primary reasons some users are unable to ascend steeper inclines actually be the "optimal configuration" of their ultralight? Would a different configuration provide better biomechanical efficiency and reduce extreme joint positions? If the answer to either of these questions is "yes", then the wheelchair really would pose a greater barrier to participation than the user's paralysis!

Given that anything higher than 4 1/2 feet off the ground is likely to be beyond the reach of many ultralight users, having to reach overhead is an unavoidable reality for most. What many clinicians may not realize is that it can be extremely difficult to “avoid positioning the hand above the shoulder” during many activities that do not involve overhead reaching when they are performed in an ultralight wheelchair. The average user’s glenohumeral joint is approximately 39” above the ground when they are sitting in a wheelchair. If the height of a standard stove is 36” high, it will not be possible for the user to cook breakfast without exceeding 90° for extended periods of time.

Given the sheer magnitude of the forces and positions that are experienced in the above tasks, it should be apparent that the ultralight should play a much greater role in implementing the CPG’s. Unfortunately, its role has changed very little since the CPG’s were published 10 years ago. While the lack of innovation in ultralight designs is troublesome, what is even more concerning is the apparent acceptance by the clinical and research communities that the inherent limitations of a static configuration have somehow become the “rules” of the game. Dynamic reconfiguration could allow us to completely rewrite the rules as we know them. To understand the possibilities, it is important to differentiate between “rules” that can be changed and “laws” that must be followed.

We May Have Been Taught the Basic Laws of Physics, But We Often Fail To Apply Them

During the years which preceded the CPG’s, it was not uncommon for full time wheelchair users with SCI to receive a folding frame model which had a significant amount of flex, used low quality components, and weighed over 50 pounds. While this is no longer the case, there continues to be a misperception about the relationship between the weight of the wheelchair and the concept of rolling resistance.

A 10 lb. difference in weight may be noticeable when lifting a wheelchair off the ground, but its contribution to the overall rolling resistance that must be overcome when self-propelling an occupied wheelchair is negligible. In terms of rolling resistance, it is the combined weight of the wheelchair and its user that must be considered. With a 200 lb. user, switching from a 25 lb. model to a 15 lb. model results in just a 4.5% reduction in the combined weight of the wheelchair and its user.

During real world use, rolling resistance depends more on the properties and quality of the individual components (e.g. bearings, casters, rear wheels, & tires), how precisely those components are aligned, the proportion of user’s weight that is distributed over the front casters, and the characteristics of the surface on which the chair is being propelled.

While the authors agree that no wheelchair should be even an ounce heavier than necessary, selecting individual components on the basis of weight alone would be of little benefit to the end user. Standard options, such as narrow 3” rollerblade casters or anodized pushrims, may be the lightest components, but they will do little to reduce rolling resistance or prevent repetitive motion injuries during everyday use. A 4”x1.5” aluminum hub soft roll caster might be heavier, but provides less rolling resistance on most surfaces. Ergonomic pushrims weigh more, but can significantly reduce the risk

of repetitive use syndromes. Similarly, any benefits provided by using lighter frame materials (e.g. thinner walled ovalized tubing or carbon fiber) may be offset if the design of the frame is such that it prohibits the individual from using aftermarket add ons in the community.

Loading the wheelchair into a vehicle is the primary context where the weight of the wheelchair matters most--specifically the weight and form factor of the largest component. Does a 15 lb. minimally adjustable model still have a place? Absolutely. Paraplegics with lower thoracic or lumbar level injuries can frequently use more compact configurations with conservative seating angles. Many can transfer easily and have exceptional trunk control which allows them to manage their stability when they use their chair in different environments. These “angle adjustable users” will benefit less from the “user adjustable angles” that dynamic reconfiguration provides. While they can still benefit from aftermarket add ons, a lighter chair that has few moving parts will be more efficient and reduce upper limb strain when loading the chair into a vehicle.

“The Law of Mutually Exclusive Configurations”

One of the main limitations of a static configuration is that it is impossible to optimize usability in every context associated with full time wheelchair use with only one configuration. When we configure the ultralight for optimal level propulsion, the orientation of the user will be lower and farther back in the chair. If we were to configure the ultralight for maximal efficiency in contexts like inclines, transfers, functional reaching, and other functional tasks, we would find that it is frequently more beneficial to provide a configuration positions the user higher and toward the front of the chair. A static configuration will not allow both, so the CPG’s recommend that we go with the configuration for optimal propulsion. We refer to this as the “Law of Mutually Exclusive Configurations”, and it is a major problem posed by a static configuration.

To illustrate the problem, consider a user with longstanding C7 quadriplegia who presents with shoulder pain and drives a modified minivan. Examination of their wheelchair may reveal a very posterior rear axle position and a relatively high rear seat height. Their configuration provides suboptimal pushrim access and distributes a considerable amount weight over the front casters. We highly suspect that their shoulder pain is the result of pushing a wheelchair that has such a suboptimal configuration for propulsion, but the individual will not heed our suggestion to move the rear axle forward and lower the rear seat height. Why? If they do, the chair becomes too tipsy to get up their ramp and they would be unable to clear the rear wheel when they transfer. They accept the reality that their wheelchair provides a suboptimal configuration in one context to be able to retain their independence in two others. Wouldn’t it be better if we could provide two configurations instead of one?

“The Conservation of Contextual Angles”

The conservation of contextual angles holds that any changes in the key angles of the user, the ultralight, or the environment will require similar changes to angles elsewhere to offset the change. While the magnitude of this change may not always be exact, some change will be necessary.

The conservation of contextual angles can apply to the angles of just the wheelchair, the angles of just the user, or the interaction of both. The relationship of key seating angles to one another on a conventional design is readily understood. The relationship between the joint angles of the user may be obvious, but is unlikely to be appreciated unless one takes the time to think about them.

Take reach for example. When a person leans forward to reach something, the forward trunk flexion they use must be offset by a similar amount of flexion at the shoulder to keep the hand at the same height. Revisiting our previous example, if 90° of shoulder flexion is necessary for the user's hand to be at the stovetop, if it 15° of trunk flexion is used to lean forward enough for the spatula to reach the skillet, another 15° of shoulder flexion is needed to maintain the hand at the same height. Instead of needing 90° of shoulder flexion, they actually use 105° due to the need to lean forward. The greater the seat slope, the longer the frame, or the less acute the front frame angle, the farther away the user will be from the task at hand, and the greater this effect will be.

In our kitchen scenario, if the user was positioned 2-3" closer to the stovetop and sat 6" higher (i.e. the glenohumeral joint is 45" high) would they be able to make pancakes without positioning their hand above the shoulder? If so, then dynamic configuration would make it possible to implement a CPG in new way.

Changes in an environmental angle have even greater implications. One of the most significant circumstances where the conservation of contextual angles creates a problem occurs on inclines. The effective angles provided by the ultralight's seating will be changed by the same amount as the incline with a static configuration. For example, an ultralight that has a seat angle of 15° and a back angle of 92° will have an effective seat angle of 25° and an effective back angle of 102° on a 10° slope!

How are these angles "conserved"? With a static configuration, the only option for restoring these angles is to change the angles of the user. The person will need to lean forward--a lot. As the trunk flexes forward, the angles used at the shoulders, elbows, and wrists become more extreme. As a consequence, not only will it take a significant amount of force to get up the ramp, that force will need to be generated with the upper extremities in extreme joint positions. Users with higher level injuries will need to lean more if they lack the trunk extension needed to counteract gravity. At the same time, they also lose the postural support that had been provided by their backrest. This represents a scenario in which the user may be at an imminent risk for injury. Would it be beneficial to provide such users with the ability to restore their seating angles, change their pushrim orientation to lessen their joint angles, or shift their center of mass forward so that they need to lean less?

Dynamic Reconfiguration: The Next Chapter

The authors have gone to significant lengths to describe the problems caused by a static configuration in secondary contexts of use. We have presented a number of common sense "rules" that may seem to state the obvious. Yet, somehow, what can seem obvious can easily be overlooked when people conceptualize the configuration of the ultralight wheelchair. Dynamic reconfiguration could allow us to rewrite the rules in ways that could allow us to implement the upper limb CPG's much more effectively than is possible today.

Throughout this paper, the author's have posed several rhetorical questions--each of which suggests a possibility that would be completely outside the realm of the ultralight having a static configuration. Obviously, we would never have posed those questions unless we actually believed that dynamic reconfiguration could provide answers to those questions. We truly believe that it can.

How do we know?

We have been fortunate enough to have firsthand experience using wheelchairs that provide such capabilities. During our presentation, we will be demonstrating this potential using two ultralight rigid frame wheelchairs that provide dynamic reconfiguration. One is a commercially available model designed to provide the user with 10" of dynamic rear seat adjustment and 30° of dynamic back angle adjustment. The second ultralight is based on another commercially available model which has been modified to provide 2.5" of fore/aft seat adjustment and 2.5" of wheelbase adjustment. Both wheelchairs allow the user to perform these adjustments "on the fly" without getting out of the chair.

Just what becomes possible when we provide the user with those ranges of dynamic adjustability?

While the authors don't know what the full potential might be, it is much more than we ever imagined. We hope that this paper has sufficiently piqued the interest of those who will attend our presentation.

The evolution of the ultralight manual wheelchair is far from complete!

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