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Design and Fabrication of a Prototype Coupler Component to Facilitate the Concurrent Collection of Mixing Chamber and Breath-By-Breath Metabolic Measurements

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Introduction and Problem Statement

Metabolic measurement systems, or devices that analyze the capacity of the human body to do work via respiratory system function, are a key tool in the field of sport and exercise science research. Most modern systems employ an open-circuit spirometer design that analyzes exhaled air. There are various configurations of open-circuit spirometers currently in use today. Two of the more common configurations are mixing chamber analysis and breath-by-breath analysis. Both classes of system are widely used and produce reliable results, but they each have distinct strengths and weaknesses that make them more appropriate for different settings.

Figure 1 *Parvomedics TrueOne 2400 integrated metabolic measurement system. Test subject running on a treadmill, 2017, wearing the snorkel like mask (a) which connects to the mixing chamber on a cart (b) via the connecting hose (c).*

Mixing chamber analysis functions by directing the air exhaled by a research subject into a chamber that combines several breaths before analyzing the large sample for its constituent gas concentrations. This well-respected technique has been widely used for years. The Parvomedics TrueOne 2400, shown in Figure 1, is an example of this type of system. The Parvomedics TrueOne device is comprised of a snorkel-like mouthpiece connected to a two-way valve (labelled “a” in Figure 1), which allows a subject to breathe in fresh air and then directs the subject’s exhaled breath to the mixing chamber and sensors (labelled “b” in Figure 2) via a connected hose. The Parvomedics TrueOne 2400 and other mixing chamber systems provide accurate and precise information for researchers in a laboratory setting.

The second and more recently developed class of systems use a breath-by-breath analysis technique. These systems use sensors placed directly on the subject's body to collect data on each breath taken by the subject, providing instantaneous metabolic information. Figure 2 displays the Cosmed K4b2 system, which employs this technique for taking indirect calorimetry measurements. The system collects flowrate data for each inhale and exhale with a small turbine located inside of a mask (labelled "a" in Figure 2) worn by the subject. The K4b2 system also has an air sampling tube that directs a small amount of air from each breath into a sensor package (labelled "b" in Figure 2), typically worn on the subject's body, that collects instantaneous gas concentration information on each breath taken by the subject. The Cosmed system is portable and can be used outside of the laboratory setting if desired.

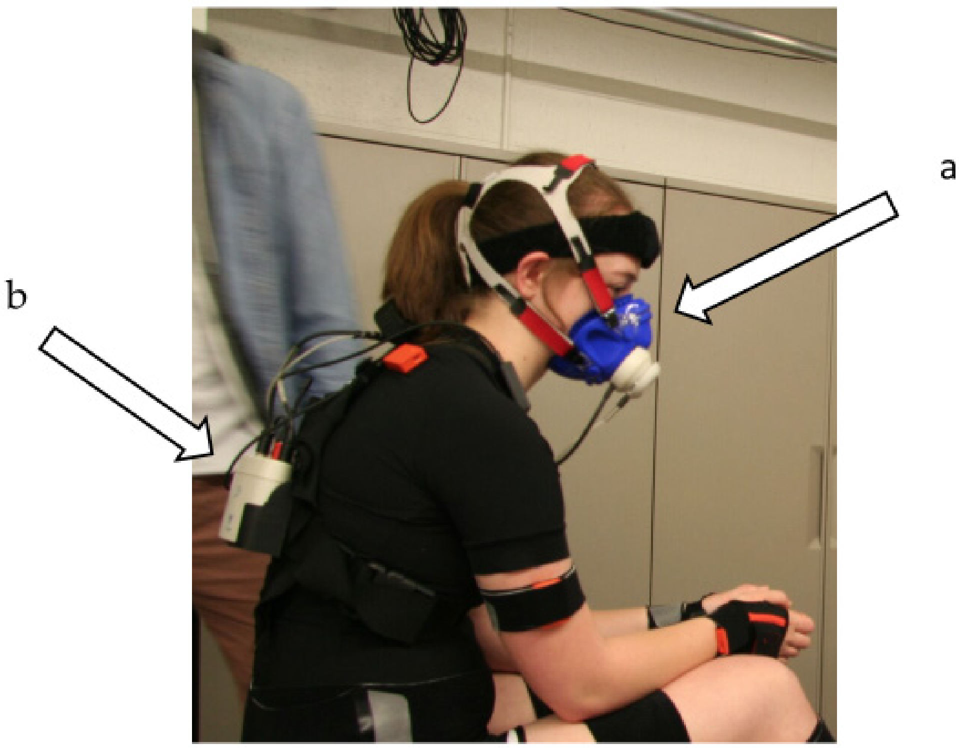

Figure 2 *Test subject wearing the Cosmed K4b2 pulmonary gas exchange measurement system, 2017. The mask (a) contains tubing that samples small volumes of air, which are analyzed in the wearable device (b).*

As previously stated, both types of systems have their uses, and the relationship between the qualities of information they collect is an area of active research (see Crouter 2006; Stroud 2009; Welch 2015). These particular studies are focused on comparing the validity of the data collected by the two types of metabolic systems in similar circumstances or using the same subjects in order to validate the usage of the breath-by-breath systems in lieu of the laboratory-based mixing chamber system. To date, there have been no attempts to collect information using both systems simultaneously on a single subject. This type of information could be very useful since the mixing chamber system and breath-by-breath systems collect information in fundamentally different ways. Data collected from both systems simultaneously could even show trends that support the use of one system over the other. Sport and exercise science researchers at Seattle University are interested in collecting just this type of information. However, fitting an exercise subject with both a breath-by-breath system and a mixing chamber system presents a key mechanical system design problem.

The critical issue, from a mechanical component point of view, is to discern how the two data collection systems can be mounted to a subject simultaneously while ensuring that the systems function as designed. The remainder of this paper will present the details of this mechanical component design problem and the solution devised by researchers in the Mechanical Engineering Department at Seattle University with the use of computer-aided design tools and 3D printing technology.

Design Problem

In order for a subject to use both the mixing-chamber TrueOne 2400 and the breath-by-breath K4b2 systems simultaneously, they must wear the data collection assemblies for both systems (labelled "a" in both Figure 1 and Figure 2) in such a way that air flows through both systems. Figure 3 shows the basic layout of the TrueOne 2400 data collection components and how air flows through the system. Note that air enters the system through a one-way check valve, moves in and out of the subject's lungs, and then flows out of a second port, through a hose, and into the mixing chamber that has sensors located on a nearby cart. The relevant K4b2 system components are shown in Figure 4. In this system, the air that a subject inhales is drawn from the outside environment and flows through an air sample tap and a small turbine prior to entering the subject's lungs. Then, when the subject exhales, the air flows back through the turbine and air sample tap, allowing for the collection of a second set of data on the same breath.

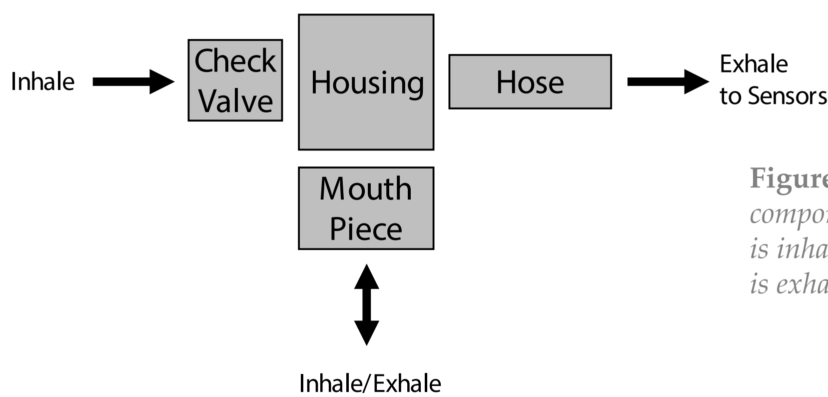

Figure 3 *Relevant TrueOne 2400 components. Air enters the system (a), is inhaled by the subject (b), and then is exhaled to the sensors (c).*

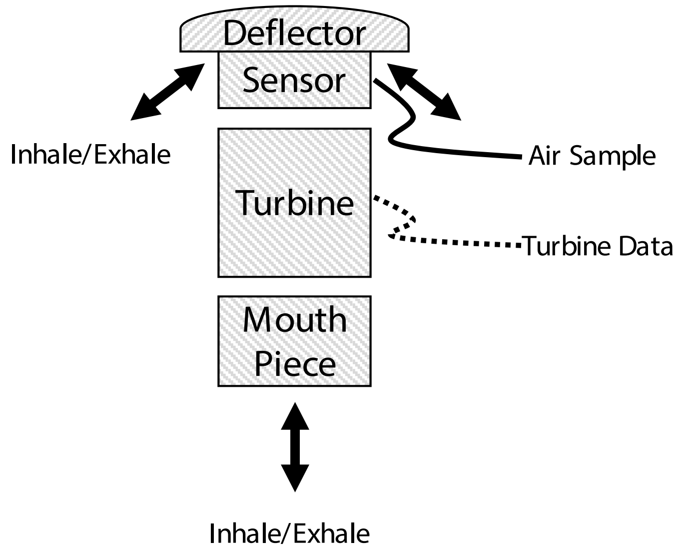

Figure 4 *Relevant Cosmed K4b2 components. Air enters the system (a), samples are taken (b), turbine data is collected (c), the air is inhaled and exhaled by the subject (d), and then passes back through the system.*

To combine these two systems for simultaneous data collection, it is necessary to allow for breath-by-breath data collection, isolating the inhaled air sample and directing all exhaled air to the mixing chamber and sensors. The proposed solution to this problem was to design a mechanical coupler that will allow for the mounting of the TrueOne 2400 valve and hose assembly onto the end of the K4b2 turbine. This physical coupler essentially connects the breath-by-breath data collection to the mixing chamber system. Figure 5 depicts this proposed coupled system, featuring a new component that facilitates the attachment of the two systems. In this coupled system, inhaled and exhaled breaths are isolated and sent to the mixing chamber, but analyzed on a breath-by-breath basis as well. Note that this new coupled system is designed purely for laboratory use.

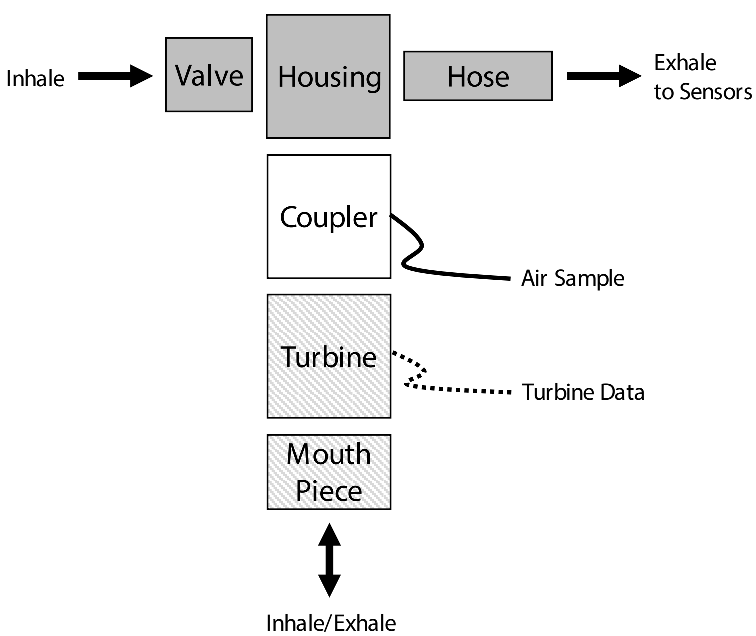

Figure 5 *Proposed coupled configuration. Air enters the system (a), samples are taken (b), turbine data is collected (c), the air is inhaled and exhaled by the subject (d), and then the exhaled air travels back through the system to the sensors (e).*

The key challenge in implementing this proposed solution is the fact that the coupler component does not exist and must be designed and fabricated in order to test the feasibility of this concept. The following requirements for this coupler component were determined jointly by sports and exercise science and mechanical engineering researchers.

1. The device should be a solid object that does not impede air flow.
2. The device should be as small and light as possible for ease of use.
3. The device should be as air-tight as possible to ensure quality of results.
4. The device must mount to the TrueOne valve assembly via the correct threaded fitting.
5. The device must mount to the K4b2 turbine via the correct press-lock fitting.
6. The device must contain a small hole and mount for attaching the K4b2 air sample hose.

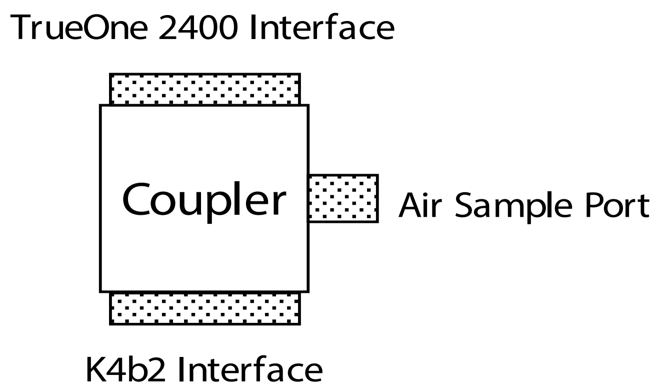

Figure 6 *Proposed coupler concept. Key design interfaces: TrueOne 2400 interface (a), air sample port (b), and K4b2 interface (c).*

Figure 6 depicts a basic conceptual design of the proposed coupler object. In Figure 6, note that the three interfaces on the coupler, also described as the attachment sites of the TrueOne 2400 and K4b2 components, are critical elements of the design.

Design Process and Prototype Solution

With the necessary requirements clearly established, mechanical engineering researchers set out to make a rough model of the coupler by taking measurements of the relevant TrueOne and K4b2 interface components. Since the attachment interfaces for each system are unique and published dimensions are not available, it was necessary to back-engineer most of the features to ensure that the coupler would have an exact fit. Once measurements were obtained, a solid model of the coupler was developed in a computer-aided design (CAD) tool called Solidworks (3D CAD Software 2015). Prototypes of the coupler designs were then fabricated with a 3D printer located in Seattle University's 3D-Printing Lab, using polylactic acid (PLA) plastic filament and the Fused Deposition Modeling (FDM) fabrication process (Gibson, Rosen and Stucker 2014).

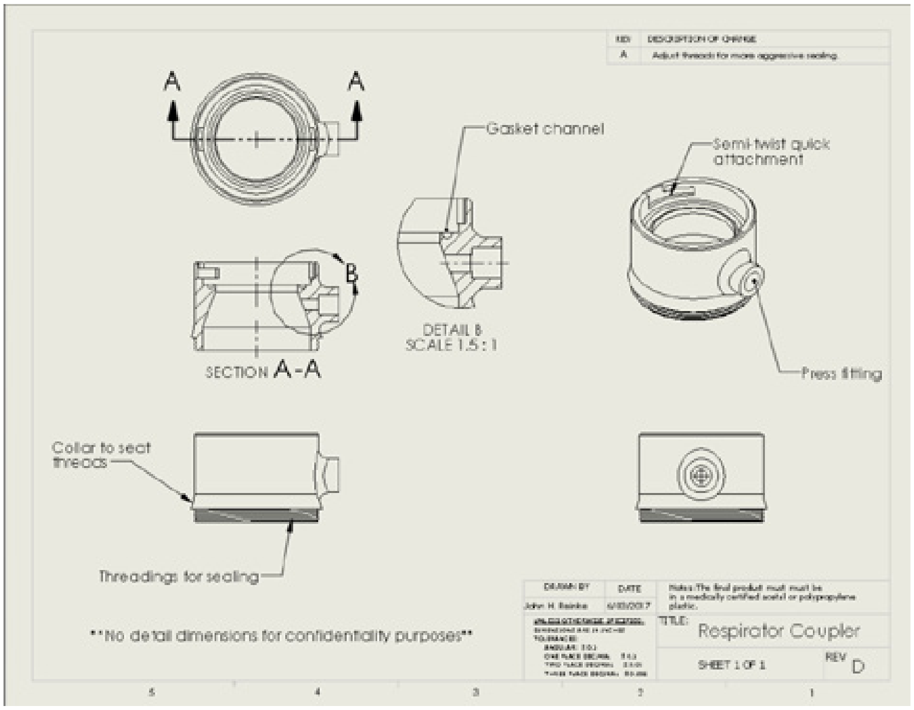

Figure 7 *Engineering drawing of the final coupler prototype.*

After an initial prototype was fabricated, the coupler was fitted to the relevant TrueOne and K4b2 components, necessary adjustments were noted, the CAD model was revised, and another prototype was produced. This process was repeated multiple times with several small changes made to the design for each successive prototype. Certain interface features were quite a challenge to recreate, and the threading required to connect to the TrueOne component presented a particular challenge. Without information available on the exact thread pattern used by the TrueOne valve assembly, it was necessary to estimate the pitch and threads per inch of the device and determine the correct geometry via a trial and error process. A total of six prototypes were printed over the course of the design project to develop a coupler with a correct fit. Figure 7 is an engineering drawing of the final coupler prototype shown in Figure 8.

Figure 8 *Isolated photo of final coupler prototype (2017). Key design features: K4b2 connection interface (a), press-fit air sampling port (b), and the TrueOne 2400 threaded-interface (c).*

Preliminary Results and Recommendations for Future Work

Once a prototype coupler design was produced, preliminary testing of the coupled operation of the two metabolic systems was conducted. These tests evaluated three metrics for each system: the volume of air exhaled per minute (VE), and the concentration of expired O2 and CO2 (FeO2, FeCO2). Preliminary results from this proof of concept testing suggest that the coupled system shows differences between the Cosmed K4b2 and the Parvomedics TrueOne 2400. Differences between the two systems are not unexpected (Stroud L.C., 2009). As Macfarlane explains in his 2001 review on automated systems, studies have observed differences in these metrics across the various systems that are commercially available (Macfarlane, D. J., 2001).

Additionally, researchers were concerned with the coupler device's mechanical operation in two ways. The first concern was that the 3D printed plastic might be porous and could leak air if pressures are high enough. Preliminary flowrate data from the coupled system does not show any significant drops when compared to the operation of the K4b2 in stock configuration. If air was leaking, a drop in flowrate would be expected. The second concern was related to the K4b2's air sampling line drawing air at a high enough rate to significantly alter the measurements taken by the TrueOne system, which operates downstream of the K4b2 in the coupled configuration. However, preliminary data does not show a reduction in air volumes measured by the TrueOne system when running in the coupled configuration as compared to the stock configuration.

The preliminary qualitative results suggest that the coupler is functioning as desired, and that the coupled system allowing for simultaneous mixing chamber and breath-by-breath analysis has the potential to collect novel sports and exercise data. These results are quite encouraging and suggest that a formal study of the new coupled system should be pursued to rigorously evaluate the function of the new coupler design.

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