Decreased exercise capacity in young athletes using self-adapted mouthguards

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Abstract

Purpose There is evidence of both the preventive effects and poor acceptance of mouthguards. There are various effects on performance depending on the type of mouthguard model. Hemodynamic responses to wearing a mouthguard have not been described. The aim of this study was to investigate the effects of self-adapted mouthguards with breathing channels (SAMGvent).

Methods In this randomized crossover study, 17 healthy, active subjects (age 25.12 ± 2.19 years) underwent body plethysmography and performed two incremental exertion tests wearing a (SAMGvent) and not wearing (CON) a mouthguard. Blood lactate, spirometrics, and thoracic impedance were measured during these maximum exercise tests.

Results The mean values using a SAMGvent revealed significantly greater airway resistance compared to CON (0.53 ± 0.16 kPa·L⁻¹ vs. 0.35 ± 0.10 kPa·L⁻¹, respectively; \( p < 0.01 \)). At maximum load, ventilation with SAMGvent was less than CON (118.4 ± 28.17 L·min⁻¹ vs. 128.2 ± 32.16 L·min⁻¹, respectively; \( p < 0.01 \)). At submaximal loads, blood lactate responses with SAMGvent were higher than CON (8.68 ± 2.20 mmol·L⁻¹ vs. 7.89 ± 1.65 mmol·L⁻¹, respectively; \( p < 0.01 \)). Maximum performance with SAMGvent was 265.9 ± 59.9 W, and without a mouthguard was 272.9 ± 60.8 W (\( p < 0.01 \)). Maximum stroke volume was higher using a SAMGvent than without using a mouthguard (138.4 ± 29.9 mL vs. 130.2 ± 21.2 mL, respectively; \( p < 0.01 \)).

Conclusion Use of a self-adapted mouthguard led to increased metabolic effort and a significant reduction in ventilation parameters. Unchanged oxygen uptake may be the result of cardiopulmonary compensation and increased breathing efforts, which slightly affects performance. These results and the obvious preventive effects of mouthguards support their use in sports.

Keywords Cardiopulmonary compensation · Ventilation · Increased airway resistance · Stroke volume

Abbreviations

ADA Access, prevention and interprofessional relations
AVDO₂ Arteriovenous oxygen difference
CAP Concurrent activation potentiation
CO Cardiac output
FetCO₂ End-tidal fractional carbon dioxide concentration
FetO₂ End-tidal fractional oxygen concentration
FEV₁ Forced expiratory volume in one second
FVC Forced vital capacity
HR Heart rate
SAMGvent Self-adapted mouthguard with breathing channels
CON Control (without mouthguard)
P_EF Peak expiratory flow
P_IF Peak inspiratory flow
RAW Airway resistance
RF Respiratory frequency
RQ Respiratory quotient
Introduction

Mouthguards (MGs) are a key factor in preventing sports-related dental injuries, especially in contact sports (Galic et al. 2018; Lässing et al. 2020b; Petrović et al. 2016). Various studies have demonstrated their preventive effect convincingly (ADA 2006; Bemelmanns and Pfeiffer 2000; Knapik et al. 2007; Lang et al. 2002; Mihalik et al. 2007). However, many athletes are very reluctant to wear mouthguards, largely because of both breathing restrictions (Amis et al. 2000; Bailey et al. 2015; Francis and Brasher 1991) and the fear of impairing performance (Caneppele et al. 2017; Delaney and Montgomery 2019). These limitations seem to depend on the model. There are two main types of mouthguards. Customized mouthguards are worn in professional sports and made individually by dentists. Inexpensive self-adapted mouthguards (SAMG) were designed for self-manufacture and widespread use, especially in youth sports (Kececi et al. 2005; Newsome et al. 2001). Some studies have postulated that using a customized mouthguard (CMG) exerts no negative effects on breathing (\( \dot{V}_E \)), oxygen uptake (\( \dot{V}O_2 \)) or maximum performance compared to wearing a conventional self-adapted mouthguard, or not (Arent et al. 2010; Caneppele et al. 2017; Duarte-Pereira et al. 2008; El-ashke and El-ashker 2015; Morales et al. 2015). In activities involving and requiring high forces or metabolic energy efficiency, even the use of a CMG has demonstrated maximum ergogenic effects (Allen et al. 2018; Buscà et al. 2018; Garner and McDivitt 2009). Described are the hypothetical effects of CMG caused by an increase in airway diameter (Garner and McDivitt 2009) showing positive effects for gas exchange (Garner 2015; Garner et al. 2011; Schulze et al. 2019a), and enhancement through the jaw repositioning associated with beneficial effects on peripheral muscle innervation (Allen et al. 2018; Arent et al. 2010; Morales et al. 2015).

Regarding SAMG use, studies reveal some \( \dot{V}_E \) restriction, but no negative effect on \( \dot{V}O_2 \) or performances (Bailey et al. 2015; Francis and Brasher 1991; Schulze et al. 2019a,b,2020). In particular, the use of a specially designed SAMG with breathing channels (SAMGvent) led to—despite lower \( \dot{V}_E \)—a lower blood lactate concentration (Bailey et al. 2015; Schulze et al. 2019a,b,2020). Yet other studies have confirmed negative effects on \( \dot{V}O_2 \), \( \dot{V}_E \), and performance from using SAMGs compared to CMG (Bourdin et al. 2006; Caneppele et al. 2017; Duarte-Pereira et al. 2008; Lässing et al. 2020b; Arx et al. 2008).

Hemodynamic parameters associated with the use of mouthguards have not been measured to date. However, documenting these cardiac parameters might give us deeper insight into the effects of self-adapted mouthguard use—effects that might be closely associated with an increase in airway resistance (Bailey et al. 2015; Francis and Brasher 1991). The use of face masks also increases airway resistance, and has shown partially altered hemodynamic parameters (Fikenzer et al. 2020; Lässing et al. 2020a). The aim of this study was therefore to investigate the influence on hemodynamic and metabolic parameters of self-adapted mouthguards with breathing channels (SAMGvent). As the effects of wearing mouthguards on pulmonary parameters are known, we would expect a negative impact on performance.

Materials and methods

Ethical approval and study group

This study was reviewed and approved by the Ethics Committee of the Medical Faculty at the University of Leipzig (file number 445-15-21122015). All subjects with infectious, orthopedic, intrinsic or other diseases were excluded from this study.

This prospective, randomized, crossover trial investigated the effects of a SAMGvent on cardiopulmonary, metabolic, and maximum power output in an ergometer step test compared to its execution without a mouthguard. The study included 17 healthy subjects (age 25.12 ± 1.9 years, weight 71.82 ± 10.50 kg and height 175.29 ± 8.04 cm). The group consisted of 8 men and 9 women who were sport students and who trained about 3.5 h a week. None of the subjects was a trained cyclist. Written informed consent was obtained from all participants. The subjects were advised not to train 24 h before the tests started, and to consume a specific amount of carbohydrates (men 10 g per kg BW and women 7 g per kg BW) to ensure that glycogen conditions remained stable.

Making of the mouthguards

The self-adapted mouthguard (Nike Adult Max Intake/Beaverton OR, USA) subjects wore is a non-customized mouthguard with breathing channels (SAMGvent). They were
warmed up in boiling water (30 s) and pressed into the upper jaw by a specialist.

**Body plethysmography**

Body plethysmography (ZAN500 Body, nSpire Health GmbH, Germany) measurements were taken with the subject wearing a mask instead of a tube (Lässing et al. 2020c).

Pulmonary airway resistance (RAW) was tested randomly without a mouthguard and with the SAMGvent. Between these randomized tests, subjects were given a 5-min break so that their respiratory muscles could recover. The body plethysmography measurements were taken with the participants wearing multi-use silicone face masks with headgear (K4b²—face mask, Cosmed, Italy). The test person in Fig. 1 gave his written informed consent allowing his image to appear in an online publication.

**Performance measures**

The incremental exercise test was performed on two different days. We allowed an at least 2-day time interval between each test day.

Each test was started with 50 W for men and 30 W for women. Wattage was increased every minute by 15 W for men and 10 W for women up to the maximum possible load. All tests were performed on a semi-recumbent independent cycle ergometer (ergometrics 900, Ergoline GmbH, Bitz, Germany) at 60–70 revolutions per minute. Cardiac output (CO), stroke volume (SV) and heart rate (HR) (measured by impedance cardiography; Physioflow, Manatec Biomedical, Manac, France), maximum oxygen consumption (VO₂ max) and respiratory parameters (VE, VT, RR) were monitored continuously at rest and during stress (K4b², Cosmed, Italy). Spirometric and thoracic impedance data were averaged for 10 s over the load.

To monitor cardiac arrhythmias, the C5-lead ECG was continuously observed to ensure the subjects’ preventive forensic safety. Blood-lactate samples (20 µL) were taken every three minutes and subjected to enzymatic-amperometric measurement (Super GL, ISO 7550, Germany). Blood pressure (BP) was measured under rest, every three minutes under stress, and after the workload. Load intensity was classified as: “rest” (0 W), “moderate” (men = 215 W/women 170 W), “submaximal” (men MW = 320 W/women MW = 210 W) and individual “maximum”.

**Calculations**

Spirometric and thoracic impedance data were recorded as the 1-min average for each load level.

We calculated alveolar ventilation (VA) by relying on the spirometrically recorded parameters that applied in these calculations (Bohr-formula): dead space volume (VD = VT × [FetCO₂ (end-tidal fractional carbon dioxide concentration) – FeCO₂ (mixed expired carbon dioxide concentration)/FetCO₂]), dead space ventilation (VD = VT × RF); alveolar ventilation (VA = (VT − VD) × RF). Breathing effort was calculated as follows: Intrapulmonary pressure = PEF × RAW. TPR was calculated: TPR = MAP/CO.

**Statistical analysis**

All values are presented as means with standard deviation. GraphPad Prism 8 (GraphPad Software Inc., California, USA) was used for statistical evaluations and graph preparation. The raw data from spirometry and impedance cardiography obtained continuously during exercise were synchronized and averaged over 10 s. The exercise parameters were then calculated for all subjects at moderate, submaximal and maximum load. For distribution analysis, the Kolmogorov–Smirnov normality test was used. If normality distribution was evident, statistical comparisons were made using paired parametric t test (body plethysmography, significance level was defined as p < 0.05) or repeated two-way ANOVA with Bonferroni’s post hoc test for multiple comparison (exercise parameter). Sphericity was determined based on the epsilon value of the Geisser greenhouse (ε). If the sphericity was rejected, Greenhouse Geisser correction would apply.

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Fig. 1 Body plethysmography measurements with spirometry masks
Results

Body plethysmography measured with mask

Table 1 illustrates pulmonary parameters in the body plethysmography measurement with mask. Pulmonary function parameters showed no differences. Only airway resistance was significantly higher with the SAMG (Table 1).

Respiratory work was calculated relying on peak flow and airway resistance parameters, which revealed significant differences (CON 2.78 ± 0.8 kPa vs. SAMG\textsubscript{vent} 4.27 ± 1.7 kPa, $p = <0.01/\eta^2_p = 0.48$).

Exercise testing

Baseline values were measured prior to each session (values not shown), and there were only TPR and $T_e$ significant differences in hemodynamics. 17 participants completed both tests. Figure 2 shows the time course of HR, SV, $V_E$ and Lac during the exercise tests with and without mouthgard. There were no significant differences in hemodynamics or metabolic parameters during moderate intensity. TPR was significantly lower at rest with SAMG\textsubscript{vent} (CON 15.62 ± 3.55 mmHg·L$^{-1}$ vs. SAMG\textsubscript{vent} 14.15 ± 2.59 mmHg·L$^{-1}$). $T_e$ was clearly prolonged under resting conditions with mouthguard use (CON 2.23 ± 1.13 s vs. SAMG\textsubscript{vent} 2.37 ± 1.12 s; $p = 0.04$). At submaximal intensity, LAC (CON 9.89 ± 1.65 mmol·L$^{-1}$ vs. SAMG\textsubscript{vent} 8.68 ± 2.20 mmol·L$^{-1}$; $p < 0.01$) and SV (CON 132.1 ± 20.9 mL vs. SAMG\textsubscript{vent} 139.4 ± 29.7 mL; $p = 0.02$) showed differences. All other measured parameters were at submaximal intensity not statistically different. Systolic and diastolic blood pressure revealed no differences throughout the exercise tests. Table 2 shows the maximum exercise parameters. The maximum power output achieved was lower with an SAMG. Pulmonary parameters differed significantly except for $VO_2$ and $V_T$. The SV was significantly increased and AVDO$_2$ decreased when wearing an SAMG\textsubscript{vent}.

Table 1  Body plethysmography measurement using the mask

| Body plethysmography | CON       | SAMG\textsubscript{vent} | $\eta^2_p$ | $p$ value |
|-----------------------|-----------|---------------------------|------------|-----------|
| $R_{AW}$ (kPa·L$^{-1}$) | 0.35 ± 0.10 | 0.53 ± 0.16 | 0.57 | $<0.01$ |
| VC (L)                | 5.06 ± 1.03 | 4.89 ± 0.95 | 0.17 | 0.09     |
| FEV$_i$ (L)           | 3.91 ± 0.65 | 3.82 ± 0.73 | 0.09 | 0.23     |
| FEV$_i$/FVC           | 79.71 ± 4.74 | 80.65 ± 4.76 | 0.08 | 0.26     |
| $P_{EF}$ (L·s$^{-1}$) | 8.19 ± 1.54 | 8.27 ± 2.23 | $<0.01$ | 0.78     |
| $P_{IF}$ (L·s$^{-1}$) | 4.39 ± 1.73 | 4.06 ± 1.84 | 0.04 | 0.49     |

Values are presented as the means and standard deviation

Significant difference in bold. SAMG\textsubscript{vent} self-adapted mouthguard with breathing channels, CON without mouthguard, SD standard deviation, VC vital capacity, $R_{AW}$ airway resistance, FEV$_i$ forced expiratory volume in one second, FVC forced vital capacity, FEV$_i$/FVC Tiffeneau–Pinelli index, $P_{EF}$ peak flow (expiratory), $P_{IF}$ peak flow (inspiratory), $\eta^2_p$ partial eta squared

Fig. 2  Tow-way ANOVA with mean values and standard deviation: a HR during rest and stress, b stroke volume during rest and stress, c ventilation during rest and stress, d lactate during rest and stress. Asterisk significant differences at the respective level
Discussion

Our study’s main finding was that wearing a self-adapted mouthguard significantly increases airway resistance ($R_{\text{AW}}$) at rest and reduces the $V_E$ during maximum load. Despite similar $\dot{V}O_2$ values, we observed a small but significantly reduced maximum ergometer performance when the SAMGvent was worn. Cardiopulmonary and metabolic parameters (Fig. 2) may indicate primarily mechanical and less peripheral neural autonomic compensation to maintain $\dot{V}O_2$ when wearing an SAMGvent.

Pulmonary parameter

Body plethysmography revealed that $R_{\text{AW}}$ rises significantly when wearing an SAMGvent. Other studies have also reported a significant or trending increase with MGs (Amis et al. 2000; Lässing et al. 2020c). Respiratory protection devices and breathing filters reveal similar effects (Lee and Wang 2011; Louhevaara 1984). Those studies demonstrate that increased $R_{\text{AW}}$ can also significantly reduce $\dot{V}E$ during exercise, and lower the athlete’s performance (Fikenzer et al. 2020; Lässing et al. 2020c; Louhevaara 1984; Melissant et al. 1998). Such significantly lower $\dot{V}E$ confirms the present study’s findings when using an SAMG (Bailey et al. 2015; Caneppele et al. 2017; Delaney and Montgomery 2019; Francis and Brasher 1991; Schulze et al. 2020). RF was also clearly reduced in conjunction with SAMGvent use, whereas $T_i$ was not influenced at maximum workload. Note that other studies have also reported lower RF with corresponding changes in breathing time when face-protection devices were used (Amis et al. 2000; Fikenzer et al. 2020; Francis and Brasher 1991; Lässing et al. 2020c; Louhevaara 1984; Schulze et al. 2020). Francis and Brasher (1991) suggest that a prolonged breathing cycle is a compensatory mechanism that can stabilize $V_T$ and the gas exchange when wearing an SAMG (Amis et al. 2000; Bailey et al. 2015; Lässing et al. 2020c). According to Francis and Brasher (1991), a mechanism resembling the ‘pursed lip’ type of breathing (PLB) in patients with obstructed breathing lengthens the respiratory cycle time. The present results demonstrate reduced $\dot{V}_A$, $\dot{V}_E$, prolonged $T_i$, and lower performance with a SAMGvent compared to

| Table 2 Exercise results with and without a self–adapted mouthguard |
|---------------------------------------------------------------|
|                  | CON                  | SAMGvent              | Adjusted p value |
| Pulmonary parameters                                      |                     |                      |                 |
| $\dot{V}O_2$ (mL·min$^{-1}$·kg$^{-1}$)          | 48.27 ± 7.13       | 48.28 ± 7.91        | >0.99           |
| FETO$_2$ (%)                                             | 16.28 ± 0.58       | 16.02 ± 0.72        | <0.01           |
| FETCO$_2$ (%)                                            | 5.07 ± 0.59        | 5.33 ± 0.63         | <0.01           |
| $V_E$ (L·min$^{-1}$)                                     | 128.2 ± 32.16      | 118.4 ± 28.17       | <0.01           |
| $\dot{V}E$ (L·min$^{-1}$)                               | 118.4 ± 32.16      | 118.4 ± 28.17       | <0.01           |
| RF (bpm)                                                  | 48.65 ± 9.23       | 44.29 ± 6.39        | <0.01           |
| $V_T$ (L)                                                 | 2.66 ± 0.45        | 2.69 ± 0.58         | >0.99           |
| $T_i$ (s)                                                 | 0.62 ± 0.10        | 0.67 ± 0.09         | 0.03            |
| $\dot{V}A$ (L·min$^{-1}$)                               | 96.90 ± 24.3       | 85.82 ± 20.6        | <0.01           |
| $T_e$ (s)                                                 | 0.68 ± 0.13        | 0.74 ± 0.12         | >0.99           |
| Hemodynamics parameters                                 |                     |                      |                 |
| HR (min$^{-1}$)                                           | 184.5 ± 8.6        | 183.2 ± 8.3         | 0.70            |
| CO (L·min$^{-1}$)                                         | 24.0 ± 3.6         | 25.2 ± 5.1          | 0.10            |
| SV (mL, n = 16)                                           | 129.8 ± 21.8       | 141.4 ± 28.0        | <0.01           |
| LAC (mmol·L$^{-1}$)                                       | 9.48 ± 1.93        | 9.47 ± 1.99         | >0.99           |
| AVDO$_2$ (%)                                              | 14.70 ± 3.09       | 14.03 ± 3.05        | <0.01           |
| TPR mmHg·L$^{-1}$                                          | 5.30 ± 0.84        | 5.12 ± 1.17         | >0.99           |
| Peak power output (W)                                     | 272.9 ± 60.8       | 265.9 ± 59.9        | 0.01            |

Values presented as the means and standard deviation; adjusted $p$ value = ANOVA with Bonferroni’s post hoc, moderate and submaximal values not shown.

Significant difference in bold. SAMGvent self-adapted mouthguards with breathing channels. CON without mouthguard, mean group mean values, SD standard deviation, $\dot{V}O_2$ oxygen uptake/min, $RF$ respiratory frequency, $V_T$ tidal volume, $V_E$ ventilation/min, $T_i$ inspiratory time, $T_e$ expiratory time, FETO$_2$ end-tidal fractional oxygen concentration, FETCO$_2$ end-tidal fractional carbon dioxide concentration, HR heart rate, $RQ$ respiratory quotient, $SV$ stroke volume, CO cardiac output, AVDO$_2$ arteriovenous oxygen difference, Lac blood lactate concentration, SBP systolic blood pressure, DBP diastolic blood pressure, $\dot{V}A$ alveolar ventilation, TPR total peripheral resistance, CW cardiac work.
CON despite similar \( \dot{V}O_2 \). The most likely explanation for these changes is the significantly increased airway resistance. Even more, the resulting greater breathing effort needed to maintain VE cancels some cardiopulmonary capacity, and might lead to distributional congruence between the respiratory and peripheral muscles (reduced AVDO\(_2\) and increased lactate) (Dominelli et al. 2017). The reduced ergometer performance despite unchanged \( \dot{V}O_2 \) may be attributable to this.

In the present study, the Fet\( O_2 \) was lower and Fet\( CO_2 \) clearly increased with the \( \text{SAMG}_{\text{vent}} \), compared to without a mouthguard. Some researchers have reported similar results, and assume an improved gas exchange rate when wearing a mouthguard (Garner et al. 2011; Schulze et al. 2020). Schulze et al. (2020) suspect that an altered jaw position favors innervation in the temporomandibular joint and associated dorsal muscle chain. They hypothesize that improved peripheral control stimulates the aerobic metabolic pathway, which may explain higher \( CO_2 \) production per breath (Schulze et al. 2020). The present results indicate minor but significantly higher lactate levels, as well as 2.6% less maximum power output using an \( \text{SAMG}_{\text{ven}} \). The obstructive breathing patterns may be the reason for higher alveolar carbon dioxide partial pressure, represented by the FET\( CO_2 \) value.

By wearing an \( \text{SAMG}_{\text{vent}} \) higher \( R_{\text{AW}} \) values lead to an altered exercise breathing pattern and significantly increased breathing capacity in healthy subjects, which limits \( V_A \) but not \( \dot{V}O_2 \) (Bailey et al. 2015; Francis and Brasher 1991; Lässing et al. 2020c; Schulze et al. 2020).

### Cardiocirculatory and metabolic parameters

There were no differences in HR parameters associated with wearing a mouthguard (Bailey et al. 2015; Delaney and Montgomery 2019; El-ashke and El-ashker 2015; Lässing et al. 2020c) in this study. Others have speculated that the PLB mechanism may influence performance when a mouthguard is worn (Amis et al. 2000; Bailey et al. 2015; Delaney and Montgomery 2019; Francis and Brasher 1991). We observed a higher SV in conjunction with \( \text{SAMG}_{\text{vent}} \) use. Respiration is known to affect the SV (Convertino et al. 2005; Fikenzer et al. 2020; Jayaweera and Ehrlich 1987; Lässing et al. 2020c; Ryan et al. 2008). Some authors suspect that a longer \( T_i \) keeps pleural pressure on a negative level for longer, and may thus favor venous return (Jayaweera and Ehrlich 1987) during mouthguard use (Lässing et al. 2020c). Other studies have shown that increased inspiratory airway resistance can raise the SV (Convertino et al. 2005; Ryan et al. 2008). Increased respiratory muscle effort because of neural-reflex mechanisms could also be responsible for the rise in SV (Harms et al. 1998; Lee and Wang 2011). Unchanged blood pressure values and similar HRs suggest a more cardiopulmonary-mechanical than neural-reflex mechanism (Ryan et al. 2008). TPR’s mean values did not differ during exertion, thus supporting the assumption of a mechanical factor rather than a neuronal effect. As respiratory resistance induced a prolonged inspiratory phase, this could presumably increase the venous return flow and thus explain the mechanically-induced higher SV with enhancing effects on the \( \dot{V}O_2 \) and maybe even the performance (Lässing et al. 2020c). The reduced AVDO\(_2\) during exercise is consistent with other studies reporting increased airway resistance when wearing face masks (Fikenzer et al. 2020; Lässing et al. 2020a). Reduced oxygen extraction caused by ventilatory obstruction has been suggested to be behind the increased lactate levels, and higher CO may due to afferent innervation from the working muscles (Blain et al. 2005; Busse et al. 1991; Harms et al. 1998). In contrast, independent studies demonstrated also the mechanical relationship between longer or higher negative pleural pressure and possible forcing effects on the transmural pressure difference in the extrathoracic and intrathoracic vessels (Convertino et al. 2005; Ryan et al. 2008) which may increase venous blood return and improve SV (Convertino et al. 2005; Fagoni et al. 2005; Ryan et al. 2008).

In summary: the wearing of an \( \text{SAMG}_{\text{vent}} \) led to an obstructed breathing pattern (Amis et al. 2000; Bailey et al. 2015; Francis and Brasher 1991; Lässing et al. 2020c) indicating slightly reduced maximum power (Caneppale et al. 2017; Duarte-Pereira et al. 2008; El-ashke and El-ashker 2015) without restricting \( \dot{V}O_2 \) (Bailey et al. 2015; Francis and Brasher 1991; Kecceci et al. 2005; Schulze et al. 2019a, 2020). Mechanical cardiopulmonary compensation may contribute to stabilizing the \( \dot{V}O_2 \) (Convertino et al. 2005; Lässing et al. 2020c; Ryan et al. 2008) which is probably higher because of the increased breathing effort while wearing a mouthguard than with no mouthguard. Nevertheless, the performance of participants wearing an \( \text{SAMG}_{\text{vent}} \) in this study revealed moderate restrictions, probably because of the respiratory muscles’ higher oxygen consumption. As a similar study (Lässing et al. 2020c) employing customized mouthguards (CMG) reported no reduction in performance, we conclude that CMGs are preferable to the \( \text{SAMG}_{\text{vent}} \) in this study.

### Study limitations

The cardiac parameters we obtained via impedance cardiology may have been overestimated using absolute values (Siebenmann et al. 2015). However, since we compared intra-individual differences and impedance cardiography is so reliable (Astorino et al. 2015; Richard et al. 2001), changes in these parameters were essential, unlike those
achieved using absolute values. Since to enable separate gender-specific data we would have needed a much larger cohort of study subjects, we cannot evaluate gender-specific differences. Nevertheless, our analyses show large homogeneity in the variation in variance of all means. Furthermore, our work does not take into account long-term adaptive regulations using a mouthguard, since the subjects wore the mouthguard only for these examinations.

Conclusion

Our investigation revealed increased airway resistance under resting conditions and significantly reduced respiratory parameters under stress in conjunction with wearing an SAMGvent. Maximum power output dropped slightly also, while the blood lactate concentration was higher. Oxygen uptake was unchanged and stroke volume improved, factors that potentially indicate cardiopulmonary compensation in combination with increased breathing effort. Nevertheless, we have demonstrated that wearing an SAMGvent reduces performance moderately—a factor that should be considered when these models are being used in sports.

Author contributions

JL and MB conceived and designed the research. JL and RF conducted the experiments. JL and RF analyzed the data. JL wrote the manuscript. All authors have read and approved the manuscript.

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Declarations

Conflict of interest

The authors have no competing interests to declare.

Ethics approval

Reference number 445-15-21122015.

Availability of data and material

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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References

ADA Council on Access, Prevention and Interprofessional Relations, ADA Council on Scientific Affairs (1939) Using mouthguards to reduce the incidence and severity of sports-related oral injuries. J Am Dent Assoc 1939 137:1712–1720. https://doi.org/10.14219/jada.archive.2006.0118 (quiz 1731)

Allen CR, Fu Y-C, Cazas-Moreno V, Valliant MW, Gdovin JR, Williams CC, Garner JC (2018) Effects of jaw clenching and jaw alignment mouthpiece use on force production during vertical jump and isometric clean pull. J Strength Cond Res 32:5–11. https://doi.org/10.1519/JSC.0000000000002172

Amit T, Di Somma E, Bacha F, Wheatley J (2000) Influence of intraoral maxillary sports mouthguards on the airflow dynamics of oral breathing. Med Sci Sports Exerc 32:284–290

Arent SM, McKenna J, Golem DL (2010) Effects of a neuromuscular dentistry-designed mouthguard on musculoskeletal and anaerobic power. Comp Exerc Physiol 7:73–79. https://doi.org/10.1017/S1755254010000231

Astorino TA, Bovee C, DeBoe A (2015) Estimating hemodynamic responses to the wingate test using thoracic impedance. J Sports Med 14:834–840

Bailey SP, Willauer TJ, Balilioglu G, Wilson LE, Salley JT, Bailey EK, Strickland TL (2015) Effects of an over-the-counter vented mouthguard on cardiorespiratory responses to exercise and physical agility. J Strength Cond Res 29:678–684. https://doi.org/10.1519/JSC.0000000000006668

Bennelmanns P, Pfeiffer P (2000) Incidence of dental, mouth, and jaw injuries and the efficacy of mouthguards in top ranking athletes. Sportverletz Sportschaden Organ Ges Orthopadisch-Traumatol Sportmed 14:139–143. https://doi.org/10.1055/s-2000-8950

Blain G, Meste O, Bermon S (2005) Influences of breathing patterns on respiratory sinus arrhythmia in humans during exercise. Am J Physiol Heart Circ Physiol 288:H887-895. https://doi.org/10.1152/ajpheart.00767.2004

Bourdin M, Brunet-Patru I, Hager J-P, Allard Y, Hager J-P, Lacour J-R, Moyen B (2006) Influence of maxillary mouthguards on physiological parameters. Med Sci Sports Exerc 38:1500–1504. https://doi.org/10.1249/01.mss.0000228952.44850.eb

Buscà B, Moreno-Doutes D, Peña J, Morales J, Solana-Tramunt M, Aguulnera-Castells J (2018) Effects of jaw clenching wearing customized mouthguards on agility, power and vertical jump in male high-standard basketball players. J Exerc Sci Fit 16(1):5–11. https://doi.org/10.1016/j.jesf.2017.11.001

Busse MW, Maassen N, Konrad H (1991) Relation between plasma K+ and ventilation during incremental exercise after glycogen depletion and repletion in man. J Physiol 443:469–476

Canepele T, Borges A, Pereira D, Fagundes A, Fidalgo T, Maia L (2017) Mouthguard use and cardiorespiratory capacity—a systematic review and meta-analysis. Sports Med Int Open 1:E172–E182. https://doi.org/10.1055/s-0043-175990

Convertino VA, Cooke WH, Lurie KG (2005) Inspiratory resistance as a potential treatment for orthostatic intolerance and hemorrhagic shock. Aviat Space Environ Med 76:319–325

Delaney JS, Montgomery DL (2019) (5) Effect of noncustom bimolar mouthguards on peak ventilation in ice hockey players [Online]. ResearchGate: [date unknown]. https://www.researchgate.net/publication/3869932_Effect_of_Noncustom_Bimolar_Mouthguards_on_Peak_Ventilation_in_Ice_Hockey_Players. Accessed 2 Feb 2019

Dominelli PB, Archiza B, Ramsook AH, Mitchell RA, Peters CM, Molgat-Seon Y, Henderson WR, Koehle MS, Boushel R, Sheel AW (2017) Effects of respiratory muscle workload on respiratory and locomotor blood flow during exercise. Exp Physiol 102:1535–1547. https://doi.org/10.1113/EP086566
Duarte-Pereira DMV, Del Rey-Santamaría M, Javierre-Garcés C, Barbany-Cairó J, Paredes-García J, Valmaseda-Castellón E, Bernini-Aytés L, Gay-Escoda C (2008) Wearability and physiological effects of custom-fitted vs self-adapted mouthguards. Dent Traumatol Off Publ Int Assoc Dent Traumatol 24:439–442. https://doi.org/10.1111/j.1600-9657.2008.00595.x

El-ashke A, El-ashker S (2015) (9) Effect of mouthguard use on metabolic and cardiorespiratory responses to aerobic exercise in males [Online]. ResearchGate. https://www.researchgate.net/publication/324744411_Effect_of_Mouthguard_Use_on_Metabolic_and_Cardiorespiratory_Responses_to_Aerobic_Exercise_in_Males

Fagoni N, Bruseghini P, Adami A, Capelli C, Lador F, Moia C, Tam E, Bringard A, Ferretti G (2020) Effect of lower body negative pressure on phase I cardiovascular responses at exercise onset. Int J Sports Med 41:209–218. https://doi.org/10.1055/a-1028-7496

Fikenzer S, Uhe T, Lavall D, Rudolph U, Falz R, Busse M, Hepp Garner DP (2015) Effects of various mouthpieces on respiratory physiology during steady-state exercise in college-aged subjects. Gen Dent 63:30–34

Francis KT, Brasher J (1991) Physiological effects of wearing mouthguards. Br J Sports Med 25:227–231

Gallic T, Kuncic D, Poklepovic Pericic T, Galic I, Mihanovic F, Bozic Fikenzer S, Uhe T, Lavall D, Rudolph U, Falz R, Busse M, Hepp Garner DP (2015) Effects of mouthpiece use on gas exchange parameters during steady state exercise in college-aged men and women. J Am Dent Assoc 193(142):1041–1047. https://doi.org/10.14219/jada.archive.2011.0325

Harms CA, Wetter TJ, McClaran SR, Pegelow DF, Nickele GA, Nelson WB, Hanson P, Dempsey JA (1998) Effects of respiratory muscle work on cardiac output and its distribution during maximal exercise. J Appl Physiol Bethesda Md 1985 85:669–685. https://doi.org/10.1152/jappl.1998.85.2.669

Jayaweera AR, Ehrlich W (1987) Changes of phasic pleural pressure in awake dogs during exercise: potential effects on cardiac output. Ann Biomed Eng 15:311–318. https://doi.org/10.1007/bf02584286

Kecceci AD, Cetin C, Erogul E, Baydar ML. (2005) Do custom-made mouth guards have negative effects on aerobic performance capacity of athletes? Dent Traumatol 21:276–280. https://doi.org/10.1111/j.1600-9657.2005.00354.x

Knapik JJ, Marshall SW, Lee RB, Darakji SS, Jones SB, Mitchener TA, delaCruz GG, Jones BH. (2007) Mouthguards in sport activities: history, physical properties and injury prevention effectiveness. Sports Med Auck NZ 37:117–144. https://doi.org/10.2165/00007370200-00003

Lang B, Pohl Y, Filipelli A (2002) Knowledge and prevention of dental trauma in team handball in Switzerland and Germany. Dent Traumatol Off Publ Int Assoc Dent Traumatol 18:329–334. https://doi.org/10.1034/j.1600-9657.2002.00123.x

Lässing J, Falz R, Pökel C, Fikenzer S, Laufs U, Schulze A, Hölddobler N, Rüdrich P, Busse M (2020a) Effects of surgical face masks on cardiopulmonary parameters and cortisol differences in a validated handball specific course. Injury. https://doi.org/10.1016/j.injury.2020.09.054

Lässing J, Schulze A, Kwast S, Falz R, Vondran M, Schrötter T, Borger M, Busse M (2020c) Effects of custom-made mouthguards on cardiorespiratory exercise capacity. Int J Sports Med 41:1–8. https://doi.org/10.1055/a-1236-3814

Lee HP, Wang DY (2011) Objective assessment of increase in breathing resistance of N95 respirators on human subjects. Ann Occup Hyg 55:917–921. https://doi.org/10.1093/annhyg/mer065

Louhevaara VA (1984) Physiological effects associated with the use of respiratory protective devices. A review. Scand J Work Environ Health 10:275–281. https://doi.org/10.5271/sjweh.2327

Melissant CF, Lammers JW, Demedts M (1998) Relationship between external resistances, lung function changes and maximal exercise capacity. Eur Respir J 11:1369–1375

Mihalik JP, McCaffrey MA, Rivera EM, Pardini JE, Guskiewicz KM, Collins MW, Lovell MR (2007) Effectiveness of mouthguards in reducing neurocognitive deficits following sports-related cerebral concussion. Dent Traumatol Off Publ Int Assoc Dent Traumatol 23:14–20. https://doi.org/10.1111/j.1600-9657.2006.00488.x

Morales J, Bussá C, Solana-Trumont M, Miró A (2015) Acute effects of jaw clenching using a customized mouthguard on anaerobic ability and ventilatory flows. Hum Mov Sci 44:270–276. https://doi.org/10.1016/j.humov.2015.09.008

Newsome PR, Tran DC, Cooke MS (2001) The role of the mouthguard in the prevention of sports-related dental injuries: a review. Int J Paediatr Dent 11:396–404. https://doi.org/10.1046/j.1939(142):1041–1047. https://doi.org/10.1016/j.jada.archive.2011.0325

N, Rüdrich P, Busse M (2020a) Effects of surgical face masks on different contact sports-water polo, karate, taekwondo and handball. Dent Traumatol Off Publ Int Assoc Dent Traumatol 34:175–181.

Accessed 22 Nov 2018

Richard R, Lonsdorfer-Wolf E, Charloux A, Doureleau S, Buchheit M, Oswald-Mammosser M, Lampert E, Mettauer B, Geny B, Lonsdorfer J (2001) Non-invasive cardiac output evaluation during a maximal progressive exercise test, using a new impedance cardiograph device. Eur J Appl Physiol 85:202–207. https://doi.org/10.1007/s004210040548

Ryan KL, Cooke WH, Richards CA, Lurie KG, Convertino VA (2008) Breathing through an inspiratory threshold device improves stroke volume during central hypovolemia in humans. J Appl Physiol Bethesda Md 1985 104:1402–1409. https://doi.org/10.1152/japplphysiol.00439.2007

Schulze A, Kwast S, Busse M (2019a) Influence of mouthguards on cardiorespiratory parameters and cortisol differences in a validated handball specific course. Injury. https://doi.org/10.1016/j.injury.2020.09.054

Schulze A, Kwast S, Busse M (2019b) Effects of a vented mouthguard on performance and ventilation in a basketball field setting. J Sports Sci Med 18:384–385

Schulze A, Laessing J, Kwast S, Busse M (2020) Influence of a vented mouthguard on physiological responses in handball. J Strength Cond Res 34:2055–2061. https://doi.org/10.1519/JSC.00000000000002596

Siebenmann C, Rasmussen P, Sørensen H, Zaar M, Hvidtfeldt M, Pichon A, Secher NH, Lundby C (2015) Cardiac output during exercise: a comparison of four methods. Scand J Med Sci Sports 25:e20–e27. https://doi.org/10.1111/smss.12201

von Arx T, Flury R, Tschan J, Buergin W, Geiser T (2008) Exercise capacity during steady state exercise in college-aged men and women. J Am Dent Assoc 139(12):1522–1530. https://doi.org/10.1111/j.1600-9657.2008.00595.x

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